Experiments in Artificial Lighting: Comparative Analysis of Luminaire Typologies

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School of Architecture
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We certify that we have read this Doctorate Project and that, in our opinion, it is satisfactory in scope and quality in partial fulfillment for the degree of Doctor of Architecture in the School of Architecture, University of Hawai'i at Mānoa.

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Abstract

"Light is not so much something that reveals, as it is itself the revelation." This statement once made by artist James Turrell articulates the primal idea that light is essential for humans to receive visual information about their surroundings. The amount of light available correlates to the amount of understanding we have of a space. As architects, we are able to alter the built environment not only through the use of form, but also through the manipulation of light.

This project aims to explore how changes to architectural lighting can create visual nuances in contrast ratios, uniformity, and illuminance levels, thereby affecting the overall visual experience of a particular space. This will be achieved through the cross-referencing of both qualitative and quantitative data, in the form of an analysis chart, using the same space to act as constant variable. This allows for visual comparison of different lighting solution impacts, as well as provides an understanding of quantitative data in a visual manner. In order to compare the different lamps, a baseline will be set using the IESNA horizontal illuminance targets. This information is then utilized to reference and compare criteria-based light evaluation systems from LEED, BREEAM and HI-CHPS. In particular, comparing and understanding how these systems excel and where they can be improved. The study proposes several guideline alterations that can be made LEED, BREEAM and HI-CHPS to further improve lighting quality in the classroom with respect to illuminance levels, illuminance uniformity, luminance, and visual contrast.

Key Terms

Ambient Lighting: the purpose of ambient lighting is to provide a general level of lighting over an entire workplane or room. Overhead fluorescent lighting is an example of ambient lighting.

CCT: Correlated Color Temperature. Refers to the color temperature of a particular light. Higher CCT values (above 5000K) are “cooler”, and tend to appear whitish-blue. Lower CCT values (2000-3000K) appear “warmer” and have a yellow appearance. CCT dictates the overall appearance and mood of a room.

Illuminance: the measurement of the amount of light energy that strikes a particular surface. Illuminance is important in providing an understanding of how much light is available to perform a particular task. Measured in foot-candles.

Illuminance Uniformity: refers to the measure of how uniform illuminance levels are over a particular surface area. Minimizing illuminance differences reduces visual distraction. Greater uniformity is preferred in office spaces and classrooms.

Illuminance Uniformity Ratio: a ratio of the average-to-minimum illuminance levels. For workspaces and classrooms, keeping a lower illuminance uniformity ratio is generally preferred.

Luminaire: commonly referred to as a light fixture. Luminaires hold lamps, ballasts, and reflectors. The design of a luminaire can affect the way light is distributed, and can reflect the architectural intent of a space.

Luminance: the measurement of the amount of light that reaches a viewer’s eye. Luminance is important in understanding glare, visual contrast, and focal point. A luminance level too high would create a glare condition, impacting visibility and task performance. Luminance is measured in footlamberts.

Photometry: the measurement of characteristics of light, including distribution pattern, light output, color temperature.

Power Density: measurement of luminaire input watts per unit area. Provides a general estimate of overall illuminance levels and energy consumption in a particular space.

Troffer: a troffer is a type of luminaire that utilize linear fluorescent lamps to provide downlighting. It is commonly used in offices and classrooms to provide general lighting. Troffers can either be mounted recessed or suspended from the ceiling.

Veiling Reflection: reflections or glare that mask the field of vision. Veiling reflections can partially or completely obscure details by reducing contrast.

Visual Contrast: visual contrast refers to the differences in luminance levels between an object and its immediate surrounding. Contrast is important in allowing the eyes to discern an object from its surroundings. Very little or very great contrast can both have negative implications on vision.

Visual Field: extent of space where objects can be seen while the eyes are stationary.

Workplane: also referred to as task plane. The workplane is the surface or imaginary plane on which tasks are performed and visual attention is placed. The task plane can either be horizontal or vertical.

01 **Introduction**

Most people would never consider driving at night without headlights. Not being able to see corners, potholes, and other potential dangers makes the idea unthinkable. Humans have an inherent need of light to understand their surroundings. As designers, we are able to alter the built environment not only using form, but also through the manipulation of light. The amount of light available correlates to the amount of understanding we have of a space. In practice, other qualities of light, such as uniformity and visual contrast play a vital role in contributing to the overall visual experience and comfort of a space. The regulation of these essential variables ensures that spaces such as classrooms have a decent level and quality of light for students to perform a wide variety of visual tasks comfortably. Code-based references such as those provided by the IESNA, provide suggested illuminance values and contrast ratios for a specific space.

These systems, while very useful for establishing a baseline, cannot accommodate the flexibility required in the multi-task nature of today's classrooms. Therefore, trade organizations such as HI-CHPS and BREEAM have developed prescribed performance criteria that new construction and retrofit applications must meet to be awarded points. The strategies defined by these guidelines specify recommended lighting levels for educational spaces (BREEAM-HEA 5, p.84), different lighting zones for general tasks and presentation tasks, and the need for individual switching controls for these zones. Notably, variables such as light distribution are otherwise not as well defined. Visual comfort is increased and eyes can perform most optimally when lighting is uniform. As such, goal-oriented design evaluation systems should define tighter strategies, adopting lighting strategies that achieve a minimum minimum-to-average uniformity ratio of 4:1 or better.

The intent of this project is to explore the nuances and repercussions that alterations in lighting can have on a space. From these explorations, the variables that have the greatest impact on the overall visual experience of a space can be elucidated. By isolating these variables, it is possible to reference and compare strategy-based evaluation systems, such as HI-CHPS and BREEAM. An analysis of these systems can provide a critical understanding of where they excel, how they can be improved.

Initial phases of the research involved utilizing Autodesk Revit, Ecotect, and Desktop Radiance lighting analysis. Computer simulations of the same architecture studio classroom were generated and analyzed with different luminaires to understand nuances and effects that changing luminaires had on the space. Initially, Revit was used to render the space with photometrically accurate IES files from manufacturers. The second phase involved testing the model in Ecotect to analyze vertical and horizontal illuminance levels on the horizontal workplane and presentation area wall to analyze foot-candle levels. Finally, false-color renderings depicting luminance levels were generated to understand changes in contrast and visual interest. The images were then compiled into a chart and briefly critiqued to narrow down the most optimal solutions based on previously researched standards.

A product of the research component of the project is a clear visual chart that allows architects to visually make comparisons and evaluations between variations between eight fluorescent retrofit, LED, and ambient-task lighting solutions. By cross-referencing both qualitative data such as rendered images, and quantitative data such as illuminance levels and contrast ratios, architects can quickly and effectively understand how a particular luminaire or lighting scheme may perform in a space. Furthermore, the understanding of how BREEAM and HI-CHPS can be challenged. For example, the chart allows for an understanding that an indirect/direct light fixture provides more uniform light. In accordance with the researched information, HI-CHPS strategy EQ.C8.1 specifies the use of "indirect/direct lighting systems for all classrooms." Through the chart, it can also be implied that by altering the spacing and number of the luminaires in addition to adding task lamps, a more economical and optimized quality of light can be obtained, which is not a component that is addressed by HI-CHPS.

This project acts as an exploration into the relationship between the technical nuances of light and how strategy-based evaluation systems can serve to better inform design decisions that will ultimately benefit the users of the built environment.

02 **Literature Review**

Introduction

Lighting in the classroom is considered to be a critical component among the numerous environmental factors that affect learning process, due to the direct relationship between good lighting and student performance.[1] As a result, the amount of literature pertaining to the various visual and non-visual aspects of lighting in the classroom is relatively extensive. By looking at the world of architectural lighting through the lens of a number of writers knowledgeable in the field, including David Egan, Victor Olgyay, and Sage Russell, it is possible to gain an understanding of the various factors that affect the luminous environment and its effects on the human visual sense, such as illuminance levels, luminance, contrast, and illuminance uniformity.

While it is challenging to document and quantify the relationship between lighting and student productivity, there is no argument that any improvement to the visual environment is beneficial to productivity. The ability to clearly see what one is doing affects the ability to effectively perform tasks. Numerous studies have been made by leading environmental psychologists and researchers, such as Jennifer Vietch, Tommy Goven, and Peter Boyce, linking productivity and the luminous environment. The findings of these studies help to provide empirical evidence towards the claims pertaining to different lighting characteristics.

Though lighting plays a prominent role in classroom and the learning experience, it is also a large contributor to the overall energy consumption of any given educational facility. According to the U.S. Department of Energy, lighting accounts for approximately 30 percent of an educational facility's overall energy consumption.[2] Thus, measures taken to reduce energy consumption would ultimately benefit administrators,

[1] Jago and Tanner 1999.
[2] U.S. Department of Energy 2004

teachers, students, and the environment. The use of a green building analysis system such as LEED allows for a level of accountability, either by the designer or client, to incorporate environmentally conscious design techniques, materials, and systems into a building. Use of such systems allows educational facilities to have a far less substantial environmental impact. Additionally, the occupants and users of a school building that has passed green building certification are exposed to a much healthier environment due to indoor environmental quality guidelines that must be met.

The following sections will look at background information regarding HI-CHPS, BREEAM, LEED, and the IESNA. The basis of each of these systems will be detailed, including goals, certification processes, and scoring. A brief comparison of similarities and differences between each system is made.

Background: HI-CHPS

The Collaborative for High-Performance Schools (CHPS) is originated as a collaborative between the California Energy commission, Pacific Gas and Electric, and San Diego Gas and Electric to improve educational facilities in California. CHPS is based off of three core principles[3]:

1) To maximize and student performance and health in the classroom
2) Conserve energy
3) Minimize waste, pollution, and environmental degradation from educational facilities.

In 2001, the Criteria for High-Performance Schools were created as a goal-setting and planning tool, and a Best Practices Manual was published by CHPS.[4] These criteria were established for twelve states, including Hawai‘i.[5] The guidelines were developed with the efforts of the CHPS board of directors, the Hawai‘i State Advisory Committee, and the public. Each state's guidelines take into account local climactic, regional, and student needs.

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[3] *HI-CHPS*, 2012. 11.
[4] *Ibid*, 6.
[5] *Ibid*, 6.

HI-CHPS consists of seven categories, grouped into three phases: Strategy, Design, and Persistence. The categories combine for a total of 171 available points. Unlike LEED and BREEAM, HI-CHPS includes prerequisites that must be achieved before each category can be considered. The seven main categories are: Integration, Indoor Environmental Quality, Energy, Water, Site, Materials and Waste Management, District Planning, Operations and Management.[6]

CHPS project scoring differs based upon whether if the project is newly constructed or a renovation. Dependent on the scores, a project can either be put into a CHPS Verified or CHPS Verified Leader certification. To be eligible for CHPS Verified, a project must meet all prerequisites and reach a minimum of 45 points (35 for renovations). CHPS Verified Leader projects must meet all prerequisites in addition to category OM.C2.1 and reach a minimum of 85 points (65 for renovations).

HI-CHPS offers three stages of certification for its projects: CHPS Designed, CHPS Verified, and CHPS Verified Leader.[7] CHPS Designed is a free certification that can be self-verified by the design team using a CHPS provided scorecard. An independent third-party assessor reviews CHPS Verified projects to ensure that all necessary requirements and prerequisites are met. Finally, CHPS Verified Leader is similar to CHPS Verified, with the exception that CHPS Verified Leader projects show sustainable design functions as incorporated into architectural expression.

HI-CHPS strengths lie in the multiple methods of verification, allowing for all types of educational projects to utilize HI-CHPS guidelines, regardless of budget or scale. Solutions such as LEED and BREEAM require a greater deal of involvement financially for projects of all scales. In its entirety, HI-CHPS offers a comprehensive set of guidelines by which better-performing educational facilities can be designed.

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[6] *HI-CHPS*, 2012. 16.
[7] *Ibid*, 12.

Background: BREEAM

Primarily used in the United Kingdom and parts of Europe, Building Research Establishment Environmental Assessment Method (BREEAM) is a green building assessment system similar to LEED in the United States. The intention of BREEAM is to become the barometer by which all sustainable construction is measured in the UK. One of the major strengths of BREEAM is that it offers guidelines for a wide variety of building typologies, ranging from offices to schools. If a particular building does not fall within any category, it can be analyzed in the BREEAM Bespoke category, where criteria are uniquely developed to suit the project.[8]

BREEAM for educational facilities consists of 10 categories: Management, Health and Well-Being, Energy, Transport, Water, Materials, Waste, Land Use/Ecology, Pollution, and Innovation.[9] Each of the categories are given a percentage weight
For educational facilities, BREEAM dictates two categories, one for K-12, and one for universities. The primary differences between the two lie in the credit weights for the Energy and Transport categories.

Due to the weighing, the scores for BREEAM are based off of percentages, rather than points. There are five levels that a BREEAM building can be placed into[10]:

Unclassified: score less than 30%
Pass: score between 30 to 45%
Good: score between 45 to 55%
Very Good: score between 55 to 75%
Excellent: score between 70 to 85%
Outstanding: greater than 85%

The BREEAM Certification process holds greater rigor as compared to that of HI-CHPS or LEED, ensuring that buildings utilizing BREEAM will firmly follow design guidelines. The seven stage certification process consists of the initial decision to follow BREEAM guidelines, appointing of a BREEAM assessor, appointing of a BREEAM

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8 *Barlow*, 2011. 15.
9 *Ibid*, 11-13.
10 *Ibid*, 14.

accredited professional, carrying out a pre-assessment prior to design, registering the project with BREEAM, carrying out the design-stage assessment, and the post-construction assessment.

The design-stage assessment is generally completed prior to starting construction. In addition, the BREEAM 2011 revision specifies that buildings that achieve a certification of Excellent or Outstanding must undergo an in-use assessment, which must take place within three years of construction completion.[11]

One of the primary differences between BREEAM and LEED is that BREEAM takes into account sustainable practices both during construction and during the building's operating cycle, whereas LEED does not offer post-occupancy review. Additionally, BREEAM caters to a wider variety of buildings through BREEAM Bespoke. BREEAM's necessity for greater financial involvement as compared to HI-CHPS can potentially limit smaller-scale, lower budget projects from becoming BREEAM-certified. However, the involvement of an accredited professional ensures that guidelines are being met at every stage of the construction process, and post-occupancy evaluations ensure that the project is performing up to standards, even after initial construction.

Background: LEED

Leadership in Efficiency and Environmental Design (LEED) is a point-based green building assessment system first introduced by the United States Green Building Council (USGBC) in 1998.[12] Since then, LEED has set precedents for green building, making it one of the most widely accepted green building assessment program in the United States.[13]

In order to address sustainable design and construction for K-12 educational facilities, LEED for Schools was developed. The latest revision of LEED for Schools

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[11] *Barlow*, 2011. 14.
[12] *Kubba*, 2012. 14.
[13] *Kubba*, 2012. 15.

was published in 2009.[14] The guidelines are based on LEED for New Construction with particular focus on classroom acoustics and master planning.

LEED is comprised of five credit categories, each given a number of awardable credits for meeting criteria. The categories consist of: Sustainable sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, and Indoor Environmental Quality. LEED is weighted by varying the number of points available in each category, depending on importance. There is a total of 100 points possible, with an additional 10 optional points awarded dependent on the region and the building's design.

LEED buildings are certified on a four-tier scale, dependent on the number of points received in each category. Below is a breakdown of the certification levels:

LEED Certified: 40 to 49 points

LEED Silver: 50 to 59 points

LEED Gold: 60 to 79 points

LEED Platinum: 80+ points

As of April 2009, LEED projects are reviewed and verified by the Green Building Certification Institute (GBCI), an independent non-profit organization supported by the USGBC.[15] Documentation for a LEED certified project is submitted to the GBCI by the architect or a LEED accredited professional.

One of the key differences between LEED, BREEAM, and HI-CHPS is that there is no post-occupancy evaluation process within LEED. Therefore, there is no method in place to ensure that the building systems are being used and maintained to optimize efficiency as intended by the designers throughout the building's life cycle. Similar to BREEAM, newer revisions of LEED require accredited professional involvement in the certification process, which ensures that guidelines are properly being met.

[14] *U.S. Green Building Council*, 2009. xii.
[15] *Ibid*, xi.

To clearly understand the use of green building analysis systems in relation to the built environment, it is important to understand what current literature offers in comparing multiple analysis systems. By comparing two or more systems, it becomes easier to understand what guidelines are common to each, and are therefore important, and which guidelines are absent or lacking in definition. To begin, the work of two writers, Sam Kubba and Tracie Reed et al. are reviewed. Both Reed et al. and Kubba have completed studies on comparing LEED and BREEAM[16] and the educational aspects of LEED and BREEAM.[17] Reed et al.'s findings in particular regard to lighting guidelines were that LEED does not indicate minimum illuminance levels, and that neither LEED nor BREEAM address lamp/luminaire efficiency from and energy conservation perspective.[18] Kubba's work provides a general overview of LEED and BREEAM, and delves into the comparison of the two systems as a whole. Unlike Reed, however, Kubba's work remains objective, and does not make any strong arguments for or against the processes and guidelines in LEED or BREEAM.

Based on the review of the background of each green building analysis system, the following table highlights the primary differences between LEED, HI-CHPS, and BREEAM:

	LEED	**BREEAM**	**HI-CHPS**
Number of Categories	7	10	5
Total Points Available	100+10	135	171
Basis of Analysis	Point Based	Weighted-Percentage	Point Based
Verification Process	Accredited Professional	Accredited Professional	Self/AP
Post Occupancy Evaluation	No	Yes	No

Table 2.1: Comparison of differences between LEED, HI-CHPS, and BREEAM

With specific regard to lighting in the educational environment, LEED, HI-CHPS, and BREEAM guidelines all commonly address the following issues:

- Provide a minimum illuminance level on the horizontal task plane (HI-CHPS and BREEAM only) [HICHPS IEQ.C8.4, 8.5; BREEAM HEA5]

[16] *Kubba*, 2012.
[17] Reed et al. 2010.
[18] *Ibid*.

- Provide means for user-controlled/occupancy based switching [HICHPS IEQ.C8.1; LEED Design Guidelines; BREEAM HEA6]
- Provide for at least two modes of lighting, for general and A/V tasks [HICHPS IEQ.C8.2; LEED IEQ 6.1; BREEAM HEA6]

The following sections will look at other aspects of these three systems in greater detail in relation to various lighting characteristics, such as illuminance levels, illuminance uniformity, and visual contrast.

Background: IESNA

The Illumination Engineering Society of North America (IESNA) is a scientific assembly devoted to the study of lighting in relation to architecture and its effects on human vision.[19] Unlike the green building analysis systems discussed in previous sections, the IESNA provides lighting standards for virtually all residential, institutional, office, and roadway applications. Within these standards are recommended value ranges are provided for illumination values, CCT, luminance values, among others.

According to the *IESNA Light+Design Guidebook*, minimum illumination values are determined "through a consensus process involving experienced designers and engineers."[20] Recommendations for lighting by the IESNA are guided by both review of scientific literature and practical experience.[21]

While the standards provided by the IESNA provide a range of acceptable lighting characteristic values for a given situation, limitations lie in that the IESNA guidelines are code-based and lack the flexibility that is offered by prescription-based evaluation methods that some of green building analysis systems previously discussed are able to provide. Green building analysis systems aim to inform environmentally-conscious design decisions by rating design strategies based on their potential to lessen

[19] *Russell*, 2008. 138.
[20] *Illuminating Society of North America*, 2008. 20.
[21] *The IESNA School and College Lighting Committee*, 2000. 7.

the impact of negative building practices on the environment, or promote building practices that are more environmentally conscious.

The IESNA publishes "Lighting for Educational Facilities", which provides a set of recommended standards for illuminance levels, luminance contrast and glare for common educational facilities, such as classrooms, auditoriums, offices, gymnasiums, and cafeterias. These guidelines, often referred to as RP-3-00, were last revised in 2000.[22]

Lighting Standards: Illuminance Levels

The term illuminance refers to the amount of light that strikes a task surface.[23] In the office or classroom, this surface is typically the desk or a teaching wall plane. The measurement of illuminance is important, as it allows for the quantification of the amount of light available to perform tasks. In essence, not having enough illuminance for a given task makes it difficult to perform the task. The amount of light required to perform a given task depends on the task.[24] The size of the task and amount of contrast available are also deciding factors. Thus, a large task with greater contrast, such as reading black-on-white text, requires a lesser amount of illuminance than a small task with little contrast.

It is important to understand that while illuminance is a key factor in providing an appropriate amount of light to perform a task comfortably, accurately and safely, illuminance levels should not be mistaken as the only factor that affects the user experience in the luminous environment.

Categories D and E from IESNA RP-3-00 standards for illuminance levels specify between 30 to 50 foot-candles on the horizontal workplane for the typical classroom

[22] *The IESNA School and College Lighting Committee*, 2000. 5.
[23] *Russell*, 2008. 41.
[24] *Illuminating Society of North America*, 2008. 41.

environment.[25] IESNA considers the tasks in these categories to be of "high contrast and large size" and "high contrast and small size, or tasks of low contrast and large size".[26]

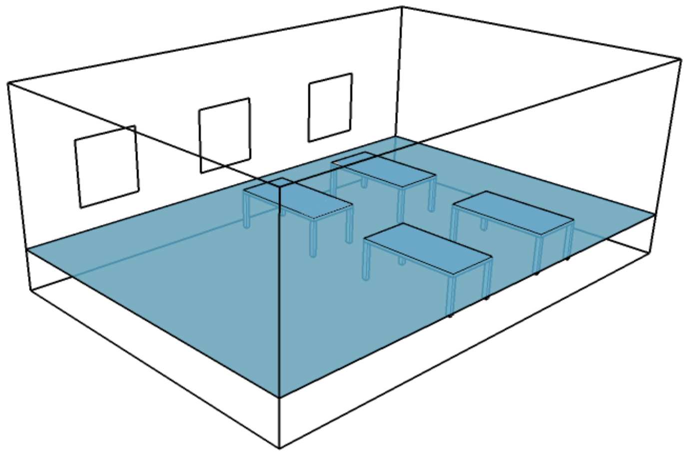

Figure 2.1: Illuminance levels are measured on an imaginary horizontal workplane 36 inches above the floor plane

In a study regarding the influence of ambient lighting on pupils in classrooms performed by Goven et al., it was found that academic test scores improved for student classrooms with increased illuminance levels and luminaire types.[27] The study consisted of two experimental classrooms, with two serving as control rooms. The control rooms utilized fluorescent ambient downlighting with illuminance levels of 300 lux (approximately 30 foot-candles), while the experiment rooms increased the illuminance levels on the workplane to 500 lux (approximately 50 foot-candles). This corresponds towards the upper end of target illuminance values for educational environments, as specified by the IESNA.

In the past, illuminance levels specified by the IESNA were higher than what was necessary, due to a "more is better" approach to illuminance, and more conservative depreciation factors for lamps.[28] From an economic point of view, increased illumination levels can increase glare issues and energy consumption, both directly and indirectly, due

[25] *Illuminating Society of North America*, 2008. 41.
[26] *The IESNA School and College Lighting Committee*, 2000. 8.
[27] *Goven et al.,* 2009.
[28] *Benya*, 2011. viii.

to internal heat gain from the usage of higher wattage lamps.[29] The argument towards a lower illuminance level comes with the presence of localized task lighting. Task lighting can prevent over-illuminating areas in the workplane.[30] Through the addition of task lights, illuminance levels can be maintained where necessary to ensure optimal task performance, while general illumination levels can be lowered to save energy and avoid over-illumination.

Similarly, wall plane illuminance levels are specified by the IESNA RP-3-00 guidelines specify a vertical illuminance of at least 30 foot-candles average on the teaching wall.[31] Wall plane illuminance levels are important for seeing tasks on the vertical plane, such as presentation materials, whiteboards, and A/V presentations.

In regards to green building analysis systems, both BREEAM (HEA5, p.84) and HI-CHPS (IEQ.C8.4, p.92) specify target illuminance levels on the desk workplane. These values are derived from the CIBSE and IESNA educational illuminance standards respectively.[32,33] For educational classrooms, the CIBSE specifies an "average of 400 lux (40 foot-candles), […] at desk height."[34] This falls in accordance with IESNA RP-03 guidelines for classrooms. In addition, HI-CHPS (IEQ.C8.5, p.92) specifies a lower target illuminance for A/V mode, between 10 and 20 maintained foot-candles.[35] Currently, LEED for Schools 2009 scheme does not provide target or minimum illuminance level guidelines. Thus, LEED for Schools should be revised to include minimum illuminance guidelines to ensure that students receive an adequate illuminance level to perform tasks. Unlike IESNA, specification of lighting guidelines in LEED would have a better means of verifying that guidelines are met through LEED project certification.

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[29] *Ibid*, x.
[30] *Egan and Olgyay*, 2002. 221.
[31] *The IESNA School and College Lighting Committee*, 2000. 7.
[32] *HI-CHPS*, 2012. 92.
[33] *BRE Global Limited*, 2012. 84.
[34] *Ibid*, 84.
[35] *HI-CHPS*, 2012. 92.

Lighting Standards: Illuminance Uniformity

All lighting produces a pattern of light and dark areas across a space, which can be detected by the human visual system.[36] Otherwise known as illuminance uniformity, this can be affected by fixtures with improper reflectors or poorly distributed luminaire spacing.[37] Extremely poor illuminance uniformity on the horizontal workplane can be seen where certain areas on the floor appear brighter while others appear to be lacking in light. With larger degrees of illuminance non-uniformity, the intermittent illuminance levels have a tendency to cause visual fatigue as the eye shifts rapidly between areas of varying illuminance.[38] In lighting design, uniformity ratios are the established standard of quantifying illuminance uniformity. While uniformity standards can vary between different types of lighting and standards, illuminance uniformity metrics consider the ratio between minimum-to-average illuminance on a given workplane.

The conclusions of studies made in regards to illuminance uniformity and task performance shows that there is no direct correlation between the two. Increasing illuminance uniformity bears no improvement in task performance. For instance, a study by Slater, Perry, and Carter varied ambient lighting in a test-office environment between very uniform and very non-uniform illuminance, and found no variance in task performance for a comparison of ten different paper-based and VDT tasks.[39]

While uniformity does not affect task performance directly, studies by Veitch et al. agree that greater illuminance uniformity is preferred in office environments. In environments where there is heavy VDT usage, a higher level of illuminance uniformity is associated with less glare and veiling reflections.[40]

In a different experiment, Slater and Boyce asked participants to rate evenness of lighting (uniformity), acceptability, and comfort in an office environment. Uniformity was considered unacceptable when the uniformity ratio dropped below 0.7

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[36] *Veitch and Newsham*, 2006. 10.
[37] *Smith*, 1999. 116.
[38] *Ibid*.
[39] *Slater et al.*, 1993.
[40] *Veitch et al.,* 2005.

(approximately 8:1 average-to-minimum).[41] However, the addition of an alternative user comfort factor, such as daylighting or user controls drew attention away from the non-uniform lighting. This suggests that with higher illuminance levels (above 50 foot-candles), the need for uniformity is not nearly as critical. However, lower average ambient illuminance levels require a greater uniformity.

Despite the research surrounding illuminance uniformity as a positive asset in workplace lighting design in reducing glare, visual fatigue, and the general preference towards uniform light by employees, green building assessment systems lack well-defined guidelines towards achieving a certain level of uniformity. Of the three green building analysis systems reviewed here, only one includes a specific mention of illuminance uniformity in its guidelines. BREEAM specifies an illuminance uniformity of 0.6 on the workplane,[42] and HI-CHPS guideline IEQ.C8.6 specifies "2 levels of uniform lighting both during day and night"[43] LEED makes no reference to specifying illuminance uniformity. The reference that HI-CHPS makes to uniform lighting is subjective and could potentially be interpreted in different ways by various designers.

Lighting Standards: Luminance and Contrast

While BREEAM, LEED and HI-CHPS do not specifically specify luminance and contrast guidelines, all denote the need to provide a lighting mode for A/V or presentational functions separate from the general classroom illumination. In a presentation or A/V setting, there are generally objects or surfaces that are being actively presented. Therefore, visual focus must be drawn to the object through the manipulation of visual contrast and luminance. As noted by Sage Russell, the author of *The Architecture of Light*, one's visual system discerns detail not by the quantity of light available, but rather how bright the object is in comparison to its immediate surroundings.[44] Through this theory, it could be inferred that detail visibility increases proportionally with added contrast. That being said, it is more energy-conscious to lower

[41] *Slater and Boyce*, 1990.
[42] *BRE Global Limited*, 2012. 84.
[43] *HI-CHPS*, 2012. 92.
[44] *Russell*, 2008. 27.

the ambient illuminance level to increase contrast, rather than adding more focal light to an already bright space.

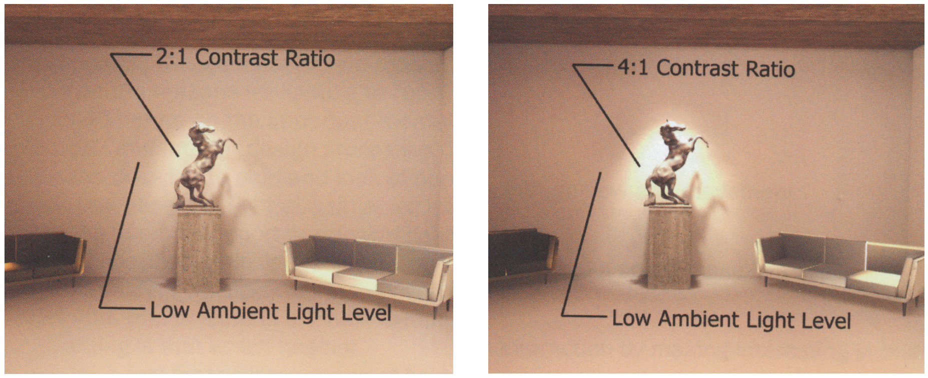

Figure 2.2: Differences in Contrast Ratio; 2:1 (left) and 4:1 (right)

To create visual emphasis, Russell recommends the use of the "two to five times" rule, where the object receiving focus has an luminance two to five times greater than its surroundings to create visual interest.[45] Examples of different contrast ratios are shown in Figure 2.2. Notice that the higher contrast ratio draws much stronger visual emphasis to the horse in the image. Interestingly, compared to Russell, David Egan recommends a more conservative 2:1 contrast ratio between surrounding surfaces and the focused object.[46] Egan states that at contrast ratios greater than 2:1 between object and surrounding surfaces, there is a loss in visual efficiency due to the eye having to adapt between to greater surrounding brightness, therefore reducing contrast.[47] Furthermore, Egan emphasizes the greater importance that luminance variability and pattern have over quantity.[48] Similar to illuminance uniformity, uneven patterns of contrast as a result of poor luminance manipulation can cause confusion and visual fatigue. In the classroom pin up gallery, poor luminance patterns can affect visual focus and how presentation materials are viewed or emphasized. Depending on the presentation and the object being focused on, a 2:1 contrast ratio may not provide enough emphasis to create sufficient visual interest. A ratio of 3:1 or greater may be necessary dependent upon the average illuminance level and the nature of the presentation task.

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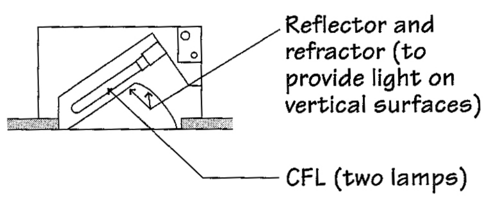
[45] *Ibid*, 137.
[46] *Egan and Olgyay*, 2002. 26.
[47] *Ibid*.
[48] *Ibid*, 20.

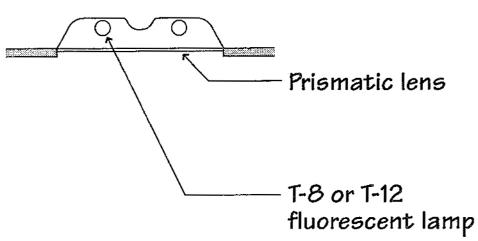
Luminaires in Offices and Classrooms

Both authors Sage Russell and David Egan provide a thorough overview of different types of luminaires, their functions, and usage in their respective literature. In the classroom and office environments, it is common to see fluorescent troffer downlighting. While these lamps provide an inexpensive, simple way of providing light, they do not provide the most optimal performance and energy consumption.[49] According to both Egan and Russell, various other luminaire options are available, including indirect luminaires, wall washers, uplights, and spotlights. Each of these luminaires provides benefits and drawbacks, depending on the usage scenario. For example, indirect lights project light upwards towards the ceiling, providing a more diffused, uniform light that is suitable for offices.[50] However, the added costs and ceiling height restrictions may influence if these luminaires are usable within a particular project. The following table illustrates commonly used lighting types in offices and classrooms, according to Russell and Egan:



Recessed

Recessed luminaires are most commonly used with point sources and wall washers. The recessed nature of the luminaire makes it one of the least visible luminaire options.



Fluorescent Troffer

Commonly used for general office lighting and corridors. Can be surface or recess-mounted. Luminaire spacing has an affect on uniformity and formation of hotspots on the horizontal workplane. Certain types of lenses may have a detrimental effect on VDT task visibility.[51]

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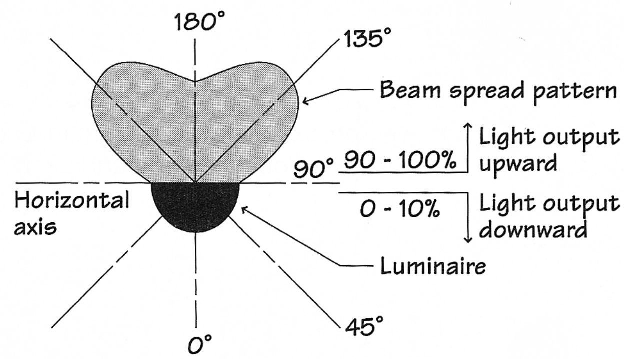
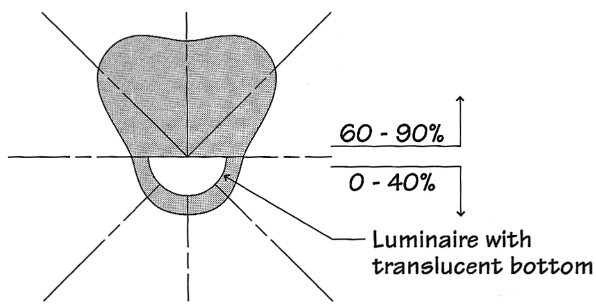
[49] *Egan and Olgyay*, 2002. 260.
[50] *Ibid*, 262.
[51] *Egan and Olgyay*, 2002. 191.



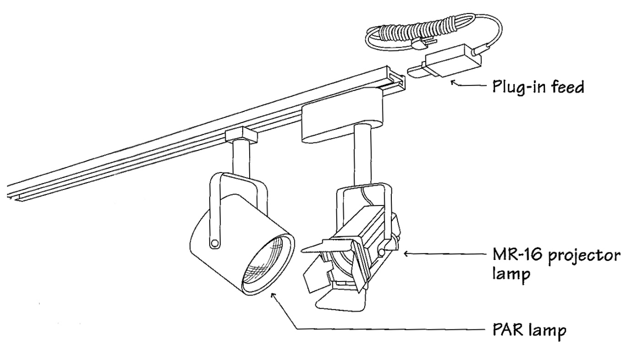
Indirect

Light is reflected from ceiling and upper walls. Can prevent dark ceilings and reduce shadows. Provides better uniformity compared to fluorescent troffers. Indirect luminaires are generally ceiling mounted. The spacing and mounting height of the luminaires affects ceiling luminance.[52]



Direct-Indirect

Direct-indirect luminaires are similar to indirect luminaires, but provide more light downward direction through a more translucent bottom opening of the luminaire. Provides similar uniformity performance as indirect luminaires.



Track

Track lamps are appropriate for gallery spaces due to provisions made for increased adjustability of the direction of light to direct attention and provide visual contrast.

Figure 2.3-2.6: Examples of different luminaire types

From these options, it can be seen that there are a wide variety of luminaires that can be used in the office and classroom environment beyond fluorescent troffers. However, it is important to note that fluorescent troffer manufacturers are constantly developing and refining the traditional troffer to match benefits found in indirect

[52] *Ibid*, 195.

luminaires. Though high cost is a limiting factor, indirect and direct-indirect luminaires are beneficial for offices and classrooms for providing uniform, diffused light. For a gallery space where the adjustability of a luminaire's direction is critical in controlling luminance contrast and patterns, track lighting provides the most advantageous solution.

As LED technology develops, increased flexibility in controlling lighting spectrum and intensity is introduced to the field of lighting.[53] Aside from lower energy consumption, LEDs allow for more control over the luminous environment, affording the ability to create more comfortable and visually appropriate lighting in the classroom.

As architects and lighting designers, understanding the differences in luminaires and their performance characteristics allows for consideration of how each luminaire may support or detract from the overall lighting design intent of a space.

Modes of Lighting: Task Lighting

Task lighting is beneficial for office and classroom lighting as it allows for task illuminance only where it is needed. For example, desk mounted task-lamps can increase desktop illuminance while information is being presented in the gallery space, allowing students to clearly see tasks without disturbing the ongoing presentation. Furthermore, task lighting allows for a reduction of overall ambient illumination, while maintaining critical illumination levels only where it is necessary, thus effectively reducing overall energy consumption.[54] When utilized in combination with ambient lighting, task lighting allows for greater flexibility in furniture placement. This is especially beneficial for architectural studio classrooms where furniture is re-arranged at the beginning of every semester to accommodate different studio needs.

Task lighting is provided through either desk mounted or furniture-integrated solutions. Desk mounted solutions are generally preferred for their future upgradability

[53] *Benya*, 2011. 112.
[54] *Illuminating Society of North America*, 2008. 14.

potential, excellent glare control, and increased user control and placement flexibility.[55] Furniture-integrated solutions help promote a clutter-free aesthetic by hiding the task luminaires, but do not provide as much upgradeability, user flexibility, glare-control, and energy-efficiency as their desk mounted counterparts.[56]

Rendering Techniques: Radiance Desktop

A majority of visual outcomes and understanding in lighting design can be understood through qualitative representations, such as a computer-generated rendering. Radiance Desktop is a powerful application used to generate highly accurate qualitative and quantitative representations of lighting. Due to its complexity, Radiance requires a relatively steep initial learning curve. Fortunately, a number of resources are available to assist with setting up and manipulating Radiance. Of particular interest is Yi Chun Huang, who provides a leading knowledge resource of Radiance through web tutorials. Huang's tutorials cover a wide variety of topics, ranging from basic Radiance setup to modeling and running simulations. Having this knowledge will assist in the simulation and modeling methodologies in this project.

Cost-Analysis Methods

Both James Benya and Sam Kubba cover cost-analysis methods through their respective literature. While both state the importance of running a cost analysis on a project and provide various cost analysis methodologies, Benya provides a much more in-depth discourse of cost analysis in relation to lighting. Kubba's chapter on cost-analysis focused primarily on incorporating green-building analysis into a cost analysis workflow, which encompassed the entire construction process. However, both mentioned that performing a cost analysis allows planners, architects, and clients to assess and compare the merits and implications of different energy-conscious construction and retrofit methods.

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[55] *Egan and Olgyay*, 2002. 366.
[56] *Ibid*.

In determining costs relative to a retrofit application, Benya divides cost-analysis into two different components: initial implementation costs and maintenance costs. Initial costs refer to the component, material, and installation labor costs incurred with both retrofit and new lighting installations.[57] Maintenance costs cover the annual cost of energy based on current electric rates and the cost of replacing lamps.

The ability to determine the cost for multiple lighting scenarios allows for direct comparison and critique of each solution based on initial implementation costs and life-cycle costs. For designers, this assists in the decision making process when selecting between luminaires. More importantly, this information can be conveyed to clients to provide justification and understanding to all available options. The manner in which Benya presents and groups his cost-analysis components provides a clear methodology of which to compare and analyze multiple lighting schemes.

Conclusion

While existing discourse has provided extensive knowledge surrounding existing green building analysis systems with particular regard to their basis and applications, the process of comparing three education facility-centric systems allows one to see areas where the guidelines for each system could be improved or revised. The comparison also allowed an examination of how each system handles the environmental factor of lighting with respect to educational facilities. Furthermore, the review of literature regarding characteristics of lighting and human factors such as: illuminance levels, illuminance uniformity, luminance, and contrast provides a strong base on which to understand, revise and define new green building assessment guidelines as a metric of ensuring that educational facilities are optimized for student learning.

LEED, BREEAM, and HI-CHPS all provide a method of accountability in providing solutions that help provide a better optimized learning environment for students while reducing environmental impact. Notably, the guidelines provided by the three systems compared herein lack consistency. For example, BREEAM and HI-CHPS

[57] *Benya*, 2011. 256.

specify illuminance guidelines, whereas LEED lacks guidelines regulating minimum illuminance levels for students. Other areas where the guidelines are lacking are guidelines for illuminance uniformity. As outlined in this chapter, illuminance uniformity is important in preventing visual distraction, fatigue, and glare. Failure to specify minimum uniformity guidelines as a metric in the development of high-performance schools could potentially result in poor uniformity, leading to non-optimal lighting for students. Finally, all three green-building analysis systems specify the importance of providing multiple modes of lighting for general and presentation tasks. However, the guidelines lack a more critical look at contrast ratios and luminance patterns. According to research previously outlined within this chapter, luminance patterns and providing a correct variation of contrast between the focal object and surroundings is essential in providing emphasis without inducing visual distractions.

Through a comparative experimental process of comparing qualitative and quantitative metrics of different lighting layouts and luminaires, it is possible to realize nuances between the performance characteristics of each scheme. A process of refinement allows for each scheme to be developed towards a goal of optimized lighting in relation to each of the lighting characteristics cited within this literature review. This allows for each of the guidelines for each green building analysis system to be refined to be optimized for student learning.

03 **Research Documentation**

Nature of Research

A majority of the research for this project is based upon computer modeling and simulation research methods. Through this methodological framework, both qualitative and quantitative performance characteristics of several lighting schemes can be efficiently and effectively analyzed. Computer and modeling simulation works well for the field of lighting design due to the ability to accurately emit and measure light rays as they react with the various surfaces inside a room. For the purpose of this study, simulation analysis will provide the most efficient and cost-effective approach to testing and analyzing a variety of different luminaires and layouts. Furthermore, it allows for alterations to be instantaneously realized and visualized as new findings are made and design objectives are refined.

The Experiment Space

This study considers a west-facing studio classroom at the University of Hawai'i School of Architecture as basis for the experimentation studies. This space is representative of a typical studio classroom at the school. The figure below shows a plan and section rendering of the space. It can be seen that the classroom has an area of approximately 3,341 square feet, with dimensions of 75'-10" by 43'-4". The height of the classroom is 13'-4" with luminaires mounted 8'-11" above the floor. The space consists of 6 window openings on the west-facing wall, with rows of luminaires that are aligned parallel to the windows.

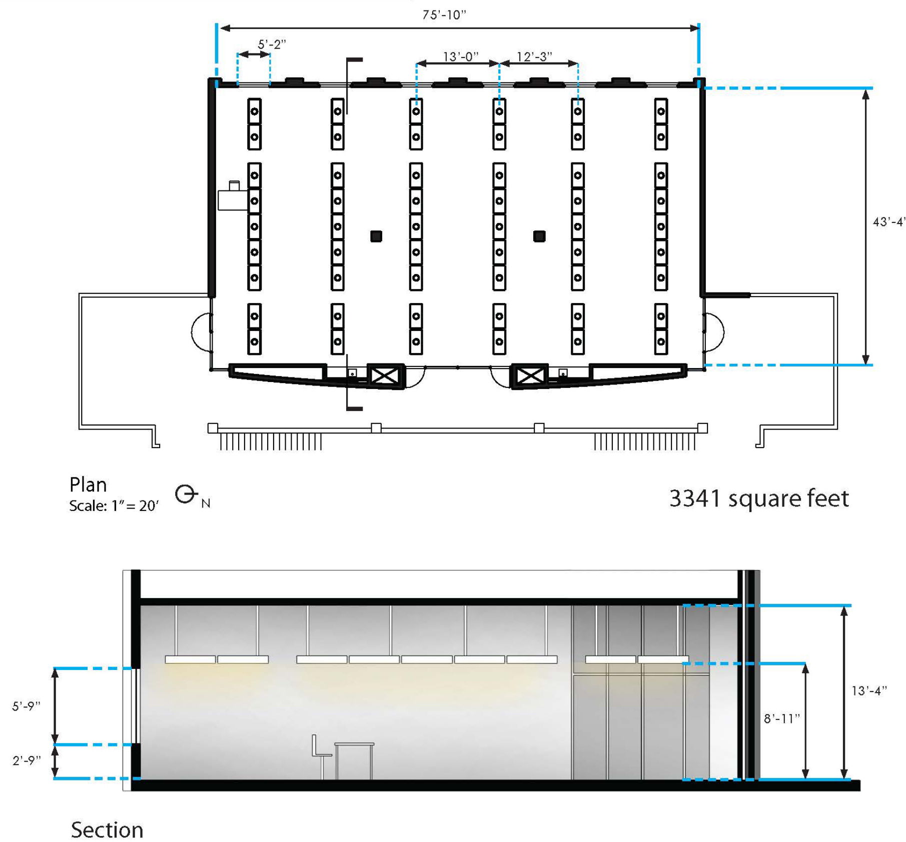

Figure 3.1: Plan and section of existing studio space to be analyzed

Research Methodology

To generate qualitative lighting visualizations that focus on portraying experiential visual qualities, a digital model of the studio classroom and surrounding context was developed using Autodesk Revit. IES photometric files and BIM models of luminaires were downloaded from respective manufacturers' websites, and lights were placed into the model according to each scheme's design. Revit was then used to generate photometrically accurate 3D renderings of different lighting schemes within the studio space from two positions, chosen to accurately represent and understand common usage scenarios of the studio space:

1) **Seated position**: the 3D camera was placed at the perspective of a student sitting down at a desk within the studio classroom.

2) **Presentation mode:** the 3D camera was placed at the perspective of a student standing while viewing a presentation at the gallery area.

To ensure that all the relevant elements in the student's visual field were represented, furniture and teaching materials modeled to have similar materiality, reflectivity, and dimensions as in the actual studio space.

Following the Revit renderings, Autodesk Ecotect building performance analysis software was employed to generate performance analyses of the individual lighting schemes. Ecotect was chosen for its ability to accurately display specific quantifiable data into the visual spectrum. Additionally, the data received from these analyses can then be comprehended and compared to established green building guidelines and educational lighting standards. The studio classroom was modeled in Ecotect with surrounding context and IES photometric files were placed as light objects, similar to the Revit model discussed earlier. An analysis grid was set at 30 inches above the floor, to simulate the workplane. For the analyses involving the teaching wall, the analysis grid was set to measure the vertical surface. The lighting performance simulations executed in Ecotect analyzed illuminance values on both the vertical and horizontal workplanes.

After completing an illuminance simulation for each scheme in Ecotect, the following values are returned:

- Illuminance distribution on the analysis grid
- Range of illuminance levels
- Average illuminance level

The ratio of average-to-minimum illuminance was calculated to show the extent of illumination uniformity as a numeric value. All of the values that were generated as a result of the simulation were then compiled and analyzed.

To complete luminance studies, Desktop Radiance allows for pixel-based luminance values to be measured after a simulation is performed. Desktop Radiance is an open-source third party plugin that works in conjunction with Ecotect. Radiance is capable of using reverse ray tracing to more accurately evaluate luminance levels.[58] Using the Ecotect model, two 3D cameras were set up in similar perspectives to those in used in the Revit model. Renderings were performed for each scheme, and a false-color image was derived using Radiance's software interface. The false color imagery provides a method of visually representing quantitative luminance data. Additionally, Radiance stores luminance level data in each of the generated image's pixels, allowing the extraction of this data by simply clicking on measurement points on the image.

A luminance image was rendered for both camera positions. Three measurement points were selected for each floor, ceiling, wall, and workplane in the rendered image. For each surface plane, the mean value of the three points was calculated. These mean values were then used to calculate contrast ratios between the immediate task plane, desk and remote wall surfaces. These values were then compared to the current IESNA RP-1-04 guidelines.

Life Cycle Costs

A life cycle cost projection for each scheme is generated to estimate initial implementation costs, as well as maintenance and operational costs over a period of one year. This allows the comparison and understanding of each lighting scheme's price versus performance. To begin understanding how each of the proposed schemes would fare economically compared to the existing lighting in the studio space, a cost projection analysis was performed. In this projection study, several economic aspects were studied for each scheme, including initial implementation costs and operating costs over the course of one year. The initial part of the cost analysis considered the estimated implementation costs, taking into account:

- Individual luminaire cost
- Lamp cost
- Cost of labor for removal of existing and installation
- Cost of additional materials necessary for installation (ballasts, wiring, controls)

[58] *Chadwell*, 2005.

To find the costs for each fixture, luminaire prices for each scheme were found at wholesale luminaire distributor, Goodmart.com.[59] Lamp prices and lamp life figures were found at 1001bulbs.com.[60] It should be noted that lamp lifetimes are based on average rated lamp life figures provided by the lamp manufacturers, and these values provide an estimation of lamp life, and can vary based on usage cycles. Labor and materials costs for each scheme were found using RSMeans project estimation cost software.[61] These costs are estimated based on national average construction costs for labor and additional materials.[62] According to RSMeans[63]:

- Labor costs were estimated at $48.63 per hour
- Installation of the relamping solutions (Schemes 2-2b) was estimated to take 54 hours, while more intensive solutions (Schemes 3-5) were estimated to take between 65 to 93 hours.
- Additional material costs ranged between $883-$1,080, depending on the scheme and level of modification necessary.

In addition to the initial costs, maintenance and operating costs were projected for each scheme, including the existing lighting layout. This provided an understanding of the potential capital outcomes of each lighting scheme. For this projection, the following factors were considered:

- Annual demand charge
- Annual energy costs
- Annual relamping costs

Energy and demand rates were gathered from Hawaiian Electric Company (HECO), using rate Schedule J for general service (effective September 1st, 2012).[64] This is the most current rate schedule for buildings that use less than 300 kW per billing period available at the time of this writing. The rate schedule indicated that general rates per

[59] Goodmart 2013
[60] 1001Bulbs 2013
[61] RS Means Company 2013
[62] Ibid.
[63] Ibid.
[64] Hawaiian Electric Company 2011

kilowatt-hour were \$0.29/kWh.[65] Demand rates were \$11.69/kW/month, which would be assessed at the end of each monthly period, based on demand hours.[66] From James Benya's book, *Lighting Retrofit and Relighting*, the following formula was used for estimating peak demand in kWh[67]:

$$Peak\ Demand\ = \frac{Watts\ per\ luminaire\ x\ Number\ of\ luminaires}{1000}$$

The result of this calculation, when multiplied by 12, yields the annual demand charge in \$/kW/month.[68]

To calculate annual energy costs, it was assumed that the lights in the studio classroom would be in operation for 10 hours per day, at 6 days per week, and 52 weeks per year. Annual energy costs were calculated using the formula[69]:

$$Annual\ energy\ cost = \frac{Operating\ hrs\ x\ Watts\ per\ luminaire\ x\ No.of\ luminaires\ x\ Electric\ energy\ rate}{1000}$$

Finally, the demand charge and annual energy costs can be added to find total annual energy cost projections. In addition to cost projections, the power density is calculated for each scheme. The power density provides a general assessment of energy consumption by providing a ratio of total watts consumed to total square footage.[70]

A table can be found in the Appendix showing a detailed breakdown of the cost projections for each scheme. In addition, all of the data from the analyzed performed are compiled into a chart that clearly depicts each scheme, and allows comparison and understanding of each of the analysis elements in relation to each scheme.

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65 Hawaiian Electric Company 2011
66 Ibid.
67 *Benya*, 2011. 223.
68 *Ibid*, 223.
69 *Ibid*, 257.
70 *Russell*, 2008. 71.

Description of Lighting Schemes

A total of 8 luminaire and lighting configurations were designed and analyzed using the aforementioned methodology. The lighting schemes were chosen and arranged based on the amount of modification necessary to implement the lighting scheme, in addition to research provided by green building assessment systems. The schemes range from least invasive to a large amount of modification necessary for implementation. A short description of the eight schemes that were developed and simulated are listed on the following pages:

SCHEME **01** EXISTING

SEATED PERSPECTIVE RENDERING

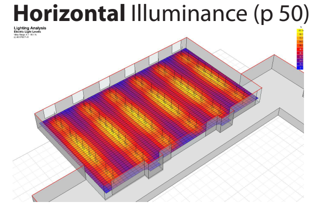
QUICK FACTS

Luminaire Make/Model	2'x4' Fluorescent Troffer
No. of Luminaires	54
Spacing	13'-0" and 12'-3" intervals
Mounting	Suspended
No. of Lamps/Wattage/Lamp Type	3 / 35w / T-12
Lumen Output	2790 lm per luminaire

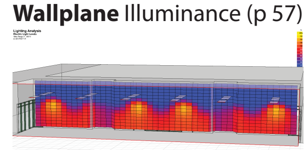
NARRATIVE

Scheme 1 focused on analyzing the existing luminaires within the studio space. **The goal of this scheme is to establish a base to compare proposed lighting scheme against.** The existing lighting layout of the studio utilizes 54 fluorescent troffers, each measuring 2' by 4'. The luminaires are suspended at 8'-11" above the finished floor. Spacing of the luminaires alternates between 13'-0 and 12'-3" intervals, with the luminaires installed perpendicular to the fenestration walls. Each parabolic luminaire contains three 35-watt T-12 lamps with a lumen output of 2790 lumens.

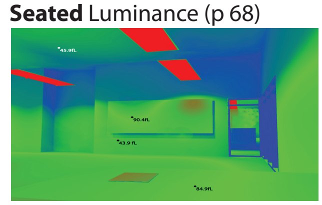
Horizontal Illuminance (p 50)



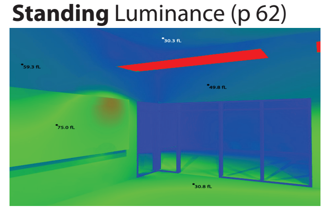
Wallplane Illuminance (p 57)



Seated Luminance (p 68)



Standing Luminance (p 62)



SCHEME **2a** T-5 RELAMP

SEATED PERSPECTIVE RENDERING

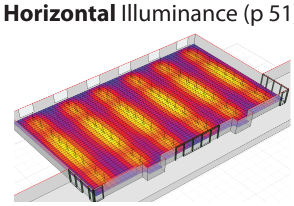
QUICK FACTS

Luminaire Make/Model	Lithonia 2RT5
No. of Luminaires	54
Spacing	13'-0" and 12'-3" intervals
Mounting	Suspended
No. of Lamps/Wattage/Lamp Type	2 / 28w / T-12
Lumen Output	

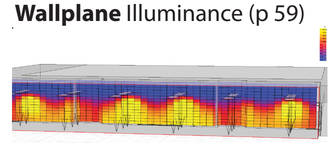
NARRATIVE

The premise of this scheme was to continue utilizing fluorescent retrofit fixtures while altering lamp types. The primary difference from scheme 2 is the use of a 2-lamp 28-watt T-5 fluorescent lamp configuration, as opposed to T-8 lamps. As in scheme 2, the T-5 retrofits use existing luminaire spacing.

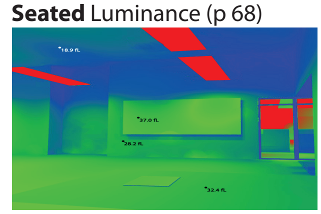
Horizontal Illuminance (p 51)



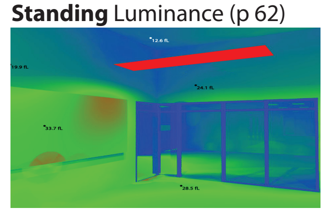
Wallplane Illuminance (p 59)



Seated Luminance (p 68)



Standing Luminance (p 62)



SCHEME **02** T-8 RELAMP

SEATED PERSPECTIVE RENDERING

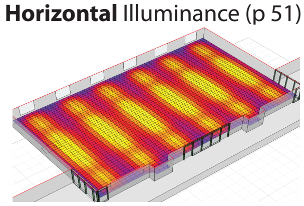
QUICK FACTS

Luminaire Make/Model	Lithonia ES8R
No. of Luminaires	54
Spacing	13’-0” and 12’-3” intervals
Mounting	Suspended
No. of Lamps/Wattage/Lamp Type	2 / 32w / T-8
Lumen Output	3100 lm per lamp

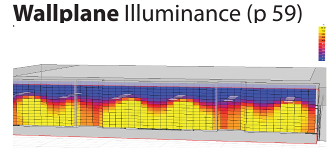
NARRATIVE

The primary goal for this scheme was to propose a solution that would allow for a quickly implementable in-place conversion of the existing T-12 fluorescent troffers into T-8 units. The intention behind the replacement was to utilize a luminaire technology that potentially consumes less energy, while maintaining existing spacing and troffer housings. Scheme 2 uses the Lithonia ES8R 2’ by 4’ relight assembly. The ES8R is a T-8 relighting system that is intended to be refitted into any existing standard parabolic troffer. The assembly uses two 32-watt T-8 fluorescent tubes, with an output of 3100 lumens per lamp.

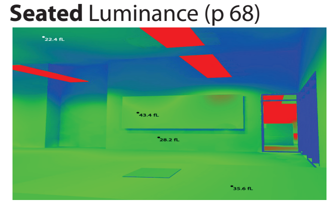
Horizontal Illuminance (p 51)



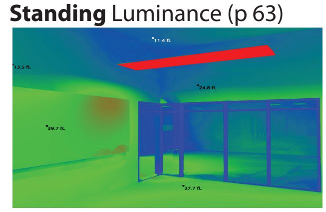
Wallplane Illuminance (p 59)



Seated Luminance (p 68)



Standing Luminance (p 63)



SCHEME **2b** LED RELAMP

SEATED PERSPECTIVE RENDERING

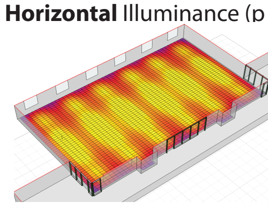
QUICK FACTS

Luminaire Make/Model	CREE CR24 LED Upkit
No. of Luminaires	54
Spacing	13’-0” and 12’-3” intervals
Mounting	Suspended
No. of Lamps/Wattage/Lamp Type	- / 44w / LED
Lumen Output	4000 lm per luminaire

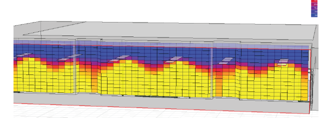
NARRATIVE

Based on LED technology, the CREE CR24 LED upkit allows for a simple, low-cost upgrade path to the latest LED technology. **This scheme allows for an understanding of how LED technology can perform in a typical relamping scenario**, revealing if the technology can be considered in the retrofitting of older fluorescent luminaires. The luminaire used in this particular scheme is the 4,000 lumen, 4,000K CCT iteration of the product.

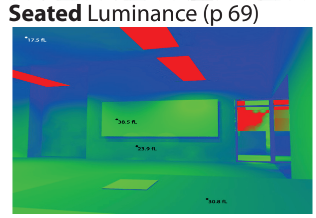
Horizontal Illuminance (p 52)



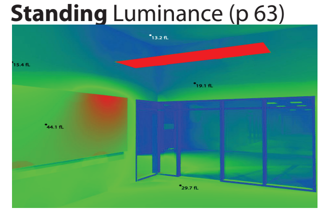
Wallplane Illuminance (p 57)



Seated Luminance (p 69)



Standing Luminance (p 63)



SCHEME **03** LED+SPACING

SEATED PERSPECTIVE RENDERING

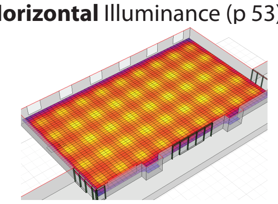
QUICK FACTS

Luminaire Make/Model	CREE CR24 LED Troffer
No. of Luminaires	45
Spacing	8'4" by 8'4"
Mounting	Suspended
No. of Lamps/Wattage/Lamp Type	- / 44w / LED
Lumen Output	4000 lm per luminaire

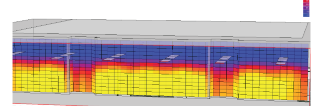
NARRATIVE

The objective of this scheme was to understand how changes to the existing luminaire layout would affect the overall illuminance pattern and uniformity on the work plane. As such, the lighting layout was altered to use 45 CREE CR24 2' by 4' troffers spaced 8'-4" apart in both length and width.

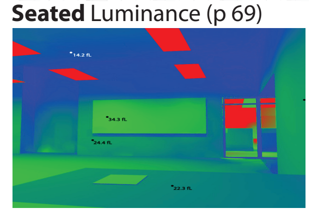
Horizontal Illuminance (p 53)



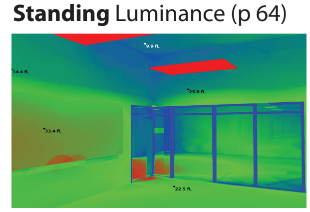
Wallplane Illuminance (p 58)



Seated Luminance (p 69)



Standing Luminance (p 64)



SCHEME **04** INDIRECT/DIRECT+TASK

SEATED PERSPECTIVE RENDERING

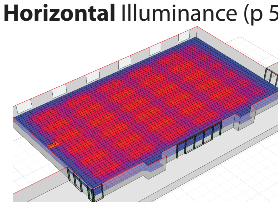
QUICK FACTS

Luminaire Make/Model	Ledalite Sona
No. of Luminaires	66
Spacing	7′-0″ and 5′-5″ intervals by 6′-5″
Mounting	Suspended
No. of Lamps/Wattage/Lamp Type	3 / 35w / T-12
Lumen Output	1436 lm (65% indirect/35% direct)
Task Luminaires	5-watt LED (desk-mounted)

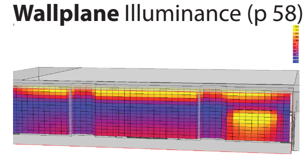
NARRATIVE

The primary goal of this scheme was to further the explorations in improving uniformity on the work plane. As such, an indirect/direct luminaire was used to provide a more even indirect illuminance on the work plane. Luminaires are mounted parallel to the fenestration walls in alternating spacing of 5′-5″ and 7′-0″ on center. The spacing of the luminaires measures 6′5″ along the north wall. The 66 Ledalite Sona luminaires used provide a 1436 lumen output of 65% indirect/35& direct each, which is provided via 3 T-5 lamps. Supplemental 5-watt LED task lamps are mounted at each desk, and additional luminaires are mounted over the pin up board to provide better illumination on the board surface.

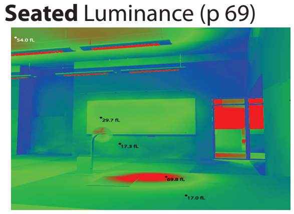
Horizontal Illuminance (p 53)



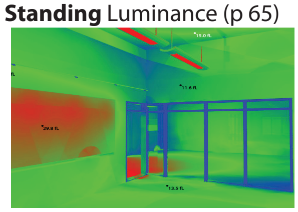
Wallplane Illuminance (p 58)



Seated Luminance (p 69)



Standing Luminance (p 65)



SCHEME **4a** INDIRECT+TASK

SEATED PERSPECTIVE RENDERING

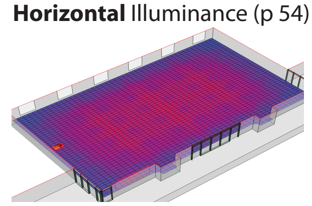
QUICK FACTS

Luminaire Make/Model	Arcos Perf II
No. of Luminaires	48
Spacing	10'-0" and 8'-0" intervals by 7'-0"
Mounting	Suspended
No. of Lamps/Wattage/Lamp Type	2 / 35w / T5HO
Lumen Output	4692 lm per luminaire (indirect)
Task Luminaires	5-watt LED (desk-mounted)

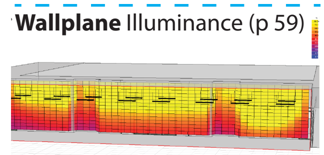
NARRATIVE

Based on outcomes of the findings in scheme 4, **the primary objectives of this scheme was to understand if a fully-indirect luminaire would offer similar levels of performance as the indirect-direct luminaire.** 48 Arcos Perf II indirect luminaires are spaced at alternating spacing of 8'-0" and 10'-0" along the fenestration wall, and 7'-0" along the north wall. The luminaire uses 2 T5HO lamps that provide a total rated lumen output of 4692. Supplemental 5-watt LED task lamps are mounted at each desk, and additional luminaires are mounted over the pin up board to provide better illumination on the board surface.

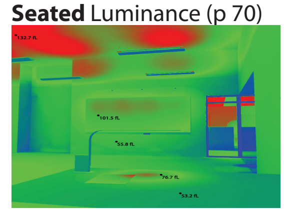
Horizontal Illuminance (p 54)



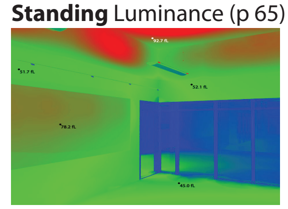
Wallplane Illuminance (p 59)



Seated Luminance (p 70)



Standing Luminance (p 65)



SCHEME **05** MULTI-SCENE

SEATED PERSPECTIVE RENDERING

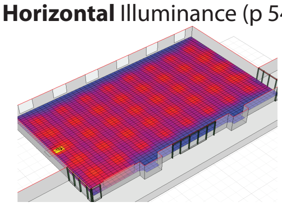
QUICK FACTS

Luminaire Make/Model	CREE CR24 LED // Philips Omega
No. of Luminaires	40 // 17
Spacing	7'6" by 9'-0" // 7'-6"
Mounting	In Suspended Ceiling
No. of Lamps/Wattage/Lamp Type	40 / 22w / LED // 17 / 36w / CFL
Lumen Output	2200 lm per luminaire

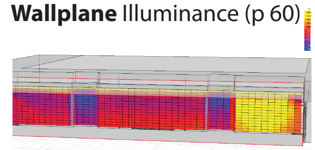
NARRATIVE

This scheme employs three types of luminaires to provide for more adaptable multi-scene lighting, in accordance to HI-CHPS guideline EQ.C8.2. The ambient lighting is provided by 40 22-watt CREE CR24 LED luminaires mounted 9'-0" along the fenestration wall and 7'-6" along the north wall. In addition, 17 36-watt Philips Omega wall washer luminaires are installed along the north walls. Supplemental task light is provided via supplemental 5-watt LED task lamps are mounted at each desk, and additional luminaires are mounted over the pin up board to provide better illumination on the board surface.

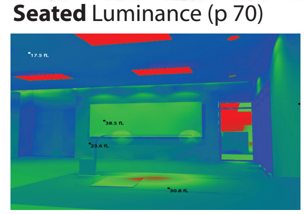
Horizontal Illuminance (p 54)



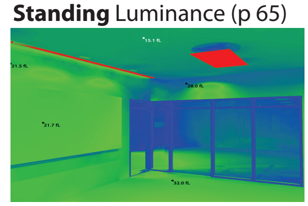
Wallplane Illuminance (p 60)



Seated Luminance (p 70)



Standing Luminance (p 65)



Results and Discussion: Rendering Analysis

Figure 3.2: Rendered Image of Scheme 1 (Existing)

Figure 3.2 above shows an image of the existing lighting in the studio space. It is immediately apparent that the light cast on the wall plane has significant areas of darkness. This indicates poor uniformity on the vertical workplane, which can become distracting under presentation and teaching situations that utilize the pin up wall. Additionally, the darker appearance of the ceiling and upper walls contributes towards an undesirable cave-like effect. A quick visual analysis also reveals that the light levels are not uniform on the desk, as seen with the desk located nearest to the pin up board.

Figure 3.3: Rendered Image of Scheme 2 (T-8 Relamp)

As seen in Scheme 2 (Fig. 3.3), the light on the pin up wall shows a noticeable improvement as compared to Scheme 1. While the board is not lit evenly, the difference between dark and light areas is not as pronounced. Additionally, the wall adjacent to the desks appears to be better lit. While the illumination on the desk is not even, the changes are between the levels is not as noticeable.

Figure 3.4: Rendered Images of Scheme 2a (T-5 Relamp)

Figure 3.4 shows a visual representation of the 2RT5 luminaire used in scheme 2a. Visual inspection reveals no significant disparities between scheme 2 and scheme 2a. However, a more critical look at the shadowed areas reveals that scheme 2a demonstrates softer shadow rendering as compared to scheme 2.

Figure 3.5: Comparison of shadows for scheme 2 (left) and 2a.

Figure 3.6: Rendered Image of Scheme 2b (LED Relamp)

Figure 3.6 above shows images of the Cree CR24 LED lamps using the existing spacing and locations. The most noticeable quality of this rendering is the change in color temperature, which is significantly cooler. Lighting uniformity on the pin up wall is most similar to that of the existing lighting, which shows a regression in uniformity on the wall plane. The lighting levels for this scheme appear to be much higher than that of previous schemes.

It should be noted at this point that while the spacing and locations of the luminaires have not changed, implementation of newer luminaire technologies have afforded an improvement in lighting quality. Noticeably, the quality of uniformity on the pin up wall and board has seen an improvement in the majority of schemes. Additionally, the illumination levels on the walls have increased, which can provide a greater sense of spaciousness.[71]

[71] *Russell*, 2008. 91.

Figure 3.7: Rendered Image of Scheme 3 (LED)

Figure 3.7 above shows the luminaires in scheme 3. The modified layout used in this scheme allows for a more uniform spread of light on the pin up wall as compared to the previous schemes. The light on the horizontal workplane appears less intense, but uniformity appears to remain the same as in previous schemes.

Figure 3.8: Rendered Image of Scheme 4 (Indirect/Direct + Task)

Figure 3.9: Rendered Image of Scheme 4a (Indirect + Task)

Figures 3.8 and 3.9 depict the most dramatic change in lighting. Here, an indirect luminaire is used in conjunction with a task lamp. It is immediately apparent that this affects the amount of light on the floor, which has been greatly reduced as compared to previous schemes. Shadows in the space appear much softer than with previous schemes.

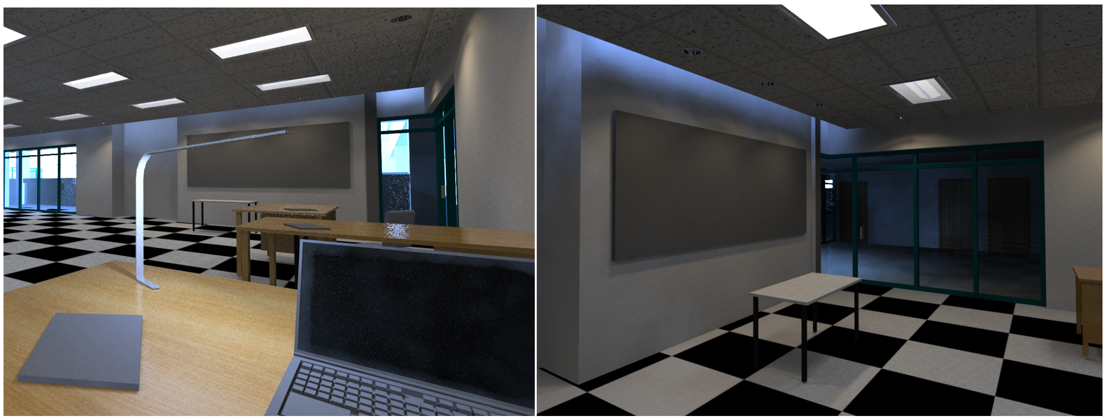


Figure 3.10: Rendered Image of Scheme 5 (Multi-Scene)

Figure 3.10 visually demonstrates scheme 5, which includes several modes of lighting to accommodate for a different variety of tasks. It can be seen that the lighting levels for this scheme remain significantly lower than that of previous schemes, which avoids the risk of over-illumination. However, the darkness of the ceiling in this scheme begins to exhibit an undesirable cave-like effect.

To summarize these findings from a visual standpoint, the existing spacing does not allow for optimized uniformity, which is especially noticeable on the pin up wall plane as hotspots of light. Visual changes on the horizontal workplane afforded by different luminaires in existing layouts show marginal improvement in uniformity, but hotspots still remain to be an issue. More invasive schemes (3-5) help to alleviate the issues of uniformity both on the wall while lowering ambient light levels. For these schemes, the lower light levels and indirect nature of the luminaires affects how shadows are cast.

A limiting factor of qualitative visualizations such as these is that they are subjectively analyzed, and cannot serve well in providing a more concrete understanding of lighting beyond a visualization tool to understand how a particular lighting scheme would appear.

The images on the following pages show a composite of all the schemes rendered during this portion of the analysis to allow for comparison purposes.

SCHEME.01 //existing

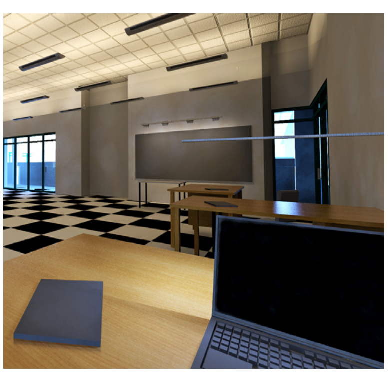
SCHEME.02 //retrofit T-8

SCHEME.02a //retrofit T-5

SCHEME.02b //retrofit LED

SCHEME.03 //LED

SCHEME.04 //direct-indirect+task



SCHEME.04a //indirect+task

SCHEME.05 //multi scene

RENDERED IMAGES - STANDING

SCHEME.01 //existing

SCHEME.02 //retrofit T-8

SCHEME.02a //retrofit T-5

SCHEME.02b //retrofit LED

SCHEME.03 //LED

SCHEME.04 //direct-indirect+task

SCHEME.04a //indirect+task

SCHEME.05 //multi scene

Results and Discussion: Illuminance – Task Plane

The baseline of evaluation for task plane illuminance is twofold:

- Meet minimum illuminance uniformity ratio (average to minimum) of 4:1 or lower.
- Maintain a minimum mean average of 30 foot-candles on the horizontal workplane, per IESNA RP-1-04[72], and HI-CHPS IEQ.C8.4.[73]

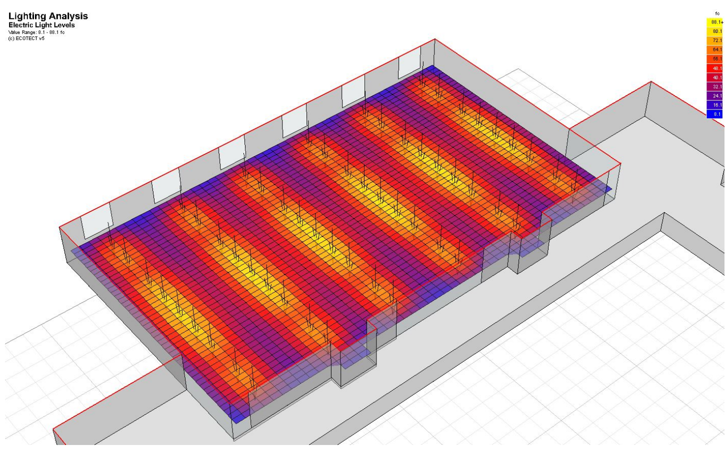


Figure 3.11: Illuminance on Task Plane - Scheme 1 (Existing)

As it stands currently, the horizontal workplane illuminance levels for the existing lighting range between 8.1 to 88.1 foot-candles. The average illuminance for this scheme is approximately 44 foot-candles over the entire workplane, which meets IESNA standards for categories E and F.[74] However, through further analysis of the pattern shown in the illuminance analysis image, it is evident that lighting uniformity is an issue with this layout. The yellow areas on the analysis grid represent hotspots on the workplane, areas of over-illuminance. These areas are concentrated towards the center of the room and graduate towards a lower illuminance level towards the edges of the room. In addition, there are areas of under illuminance between the rows of luminaires, as indicated by the blue regions in the analysis grid. The calculated average-to-minimum uniformity ratio for this scheme is 6:1, which does not meet the minimum requirements of 4:1 or lower.

[72] *Illuminating Society of North America*, 2000.
[73] *HI-CHPS*, 2012. 92.
[74] *Illuminating Society of North America*, 2000.

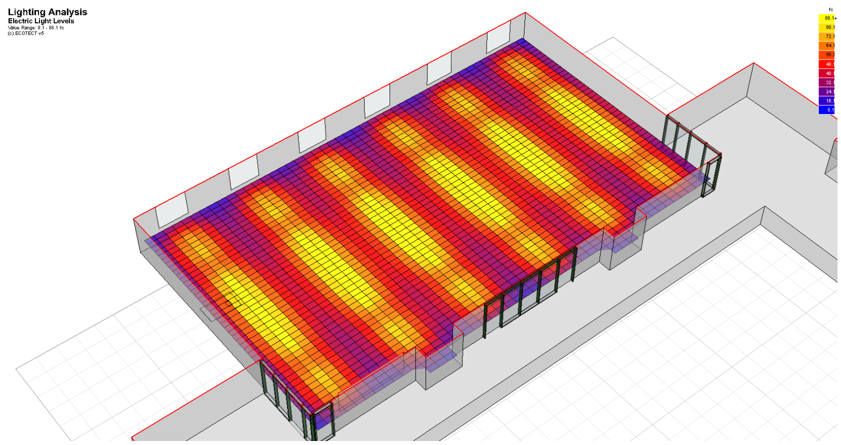


Figure 3.12: Illuminance on Task Plane - Scheme 2 (Relamp T-8)

Looking at the illuminance distribution pattern of Scheme 2 in figure 3.12, it can be seen that the areas depicted in blue are slightly decreased in size when compared to that of scheme 1. Accordingly, the calculated uniformity ratio is has decreased to 5.2, which shows a marked improvement over scheme 1. However, this does not meet the minimal requirements of illuminance uniformity of 4:1 or better. Additionally, the bands of yellow in the concentrated in the center of the room show that there is still a considerable amount of over-illumination.

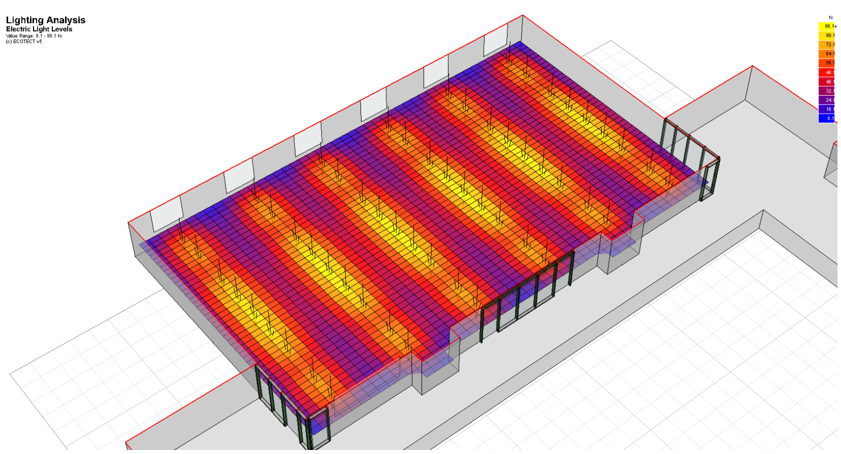


Figure 3.13: Illuminance on Task Plane - Scheme 2a (Relamp T-5)

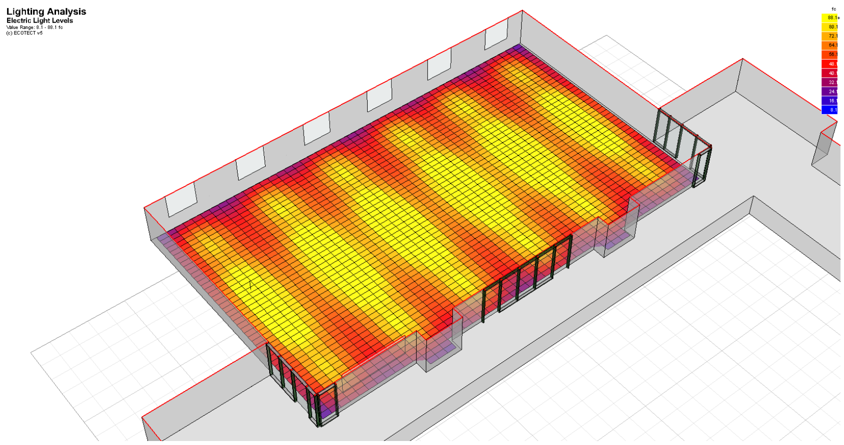


Figure 3.14: Illuminance on Task Plane - Scheme 2b (Relamp LED)

In schemes 2a and 2b, the illumination pattern shares similarities with those of previous schemes. In schemes 1 – 2b, average illumination levels ranged between 44 and 65 foot-candles, where the highest value was achieved by scheme 2b. While these average values are all in accordance to IESNA minimum standards, the illumination levels at the hotspots range within 88 foot-candles, which is not optimal. This indicates an issue with the existing luminaire layout.

Of the schemes, scheme 2b indicated the highest average illumination level of 65.98 foot-candles. This demonstrates the inflexibility with the existing luminaire layout in maintaining illuminance values in accordance to IESNA values and implementing newer lighting technologies. Installation of a higher output LED luminaire may result in undesirable gross over-illumination of the space. Combined with the illuminance hotspots inherent of the layout, scheme 2b shows the highest illuminance value of 95 foot-candles.

Moving forward with knowledge gained from these previously discussed schemes, the following schemes attempt to address the two main deficiencies in the previous 4 schemes: uniformity and over-illumination towards the center of the room.

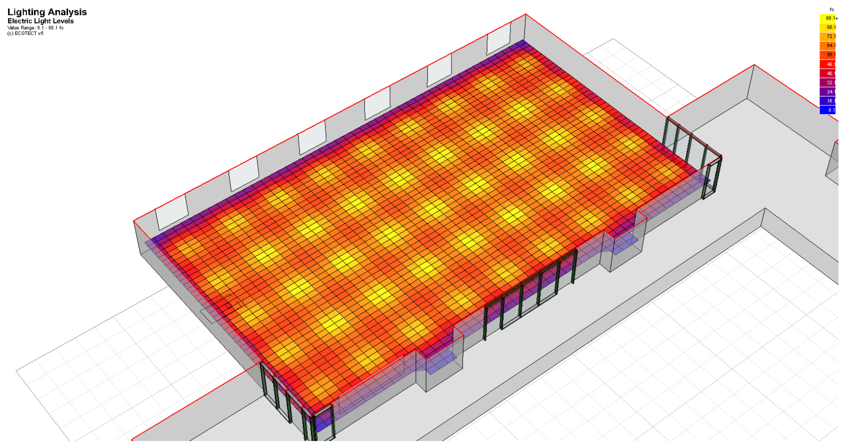


Figure 3.15: Illuminance on Task Plane - Scheme 3 (LED)

While altering the luminaire spacing and layout reduced over-illumination issues, as seen in schemes 3 and 5, the alterations both showed a regression in illuminance uniformity on the horizontal workplane as compared to the existing layout.

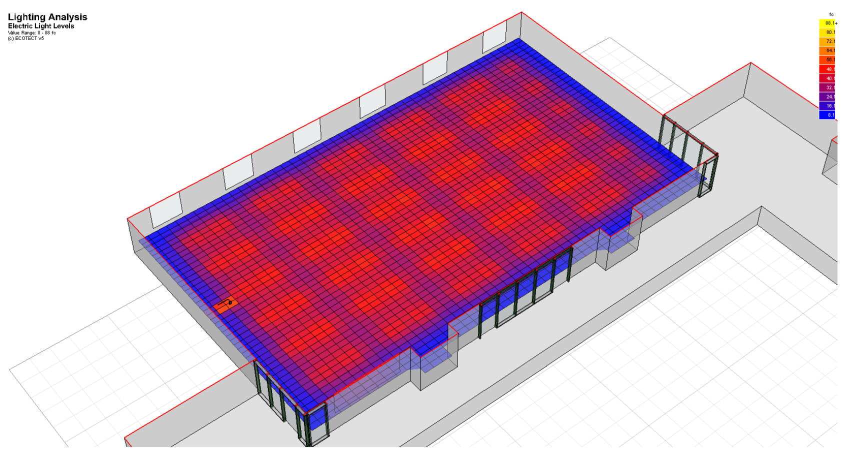


Figure 3.16: Illuminance on Task Plane - Scheme 4 (Indirect/Direct + Task)

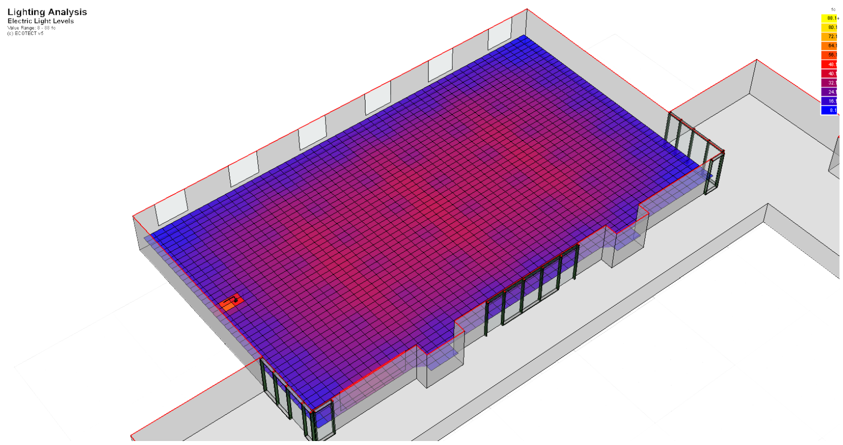


Figure 3.17: Illuminance on Task Plane - Scheme 4a (Indirect + Task)

In regards to both illumination level standards and uniformity standards, the results of this analysis show that only schemes 4 and 4a met both illumination criteria. This implies that based on the standards, illumination provided by indirect luminaires is best suited for learning environments. It is important to note that these conclusions are based on illumination studies only, and do not take into consideration other performance factors that are exhibited by these luminaires.

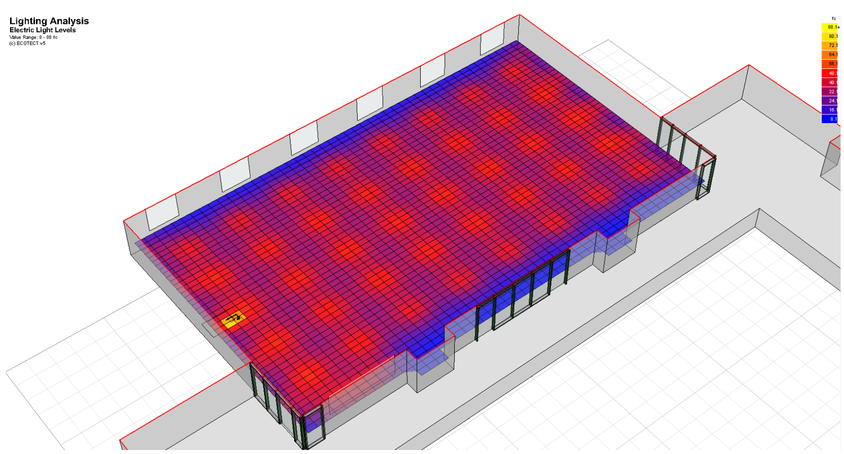


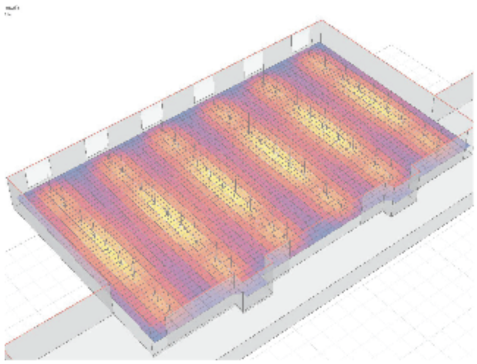
Figure 3.18: Illuminance on Task Plane - Scheme 5 (Multi-Scene)

Based on the knowledge gained from scheme 2b, scheme 5 (shown in Figure 3.18) was revised to use a lower-rated 22-watt version of the CREE CR24 luminaire. This resulted in a reduction of average illuminance levels to approximately 47 foot-candles, which falls within minimum baseline requirements while using less power.

All of the schemes tested, with the exception of 4 and 4a, did not meet uniformity standards of 4:1. This indicates that it is difficult to obtain optimal illuminance uniformity standards set by the previously mentioned guidelines, unless an indirect luminaire is used to provide ambient lighting.

The following page provides a composite of all the images generated during this analysis to allow for side-by side comparisons. Images that appear greyed-out do not meet the required baselines, as discussed previously.

ILLUMINANCE ANALYSIS - HORIZONTAL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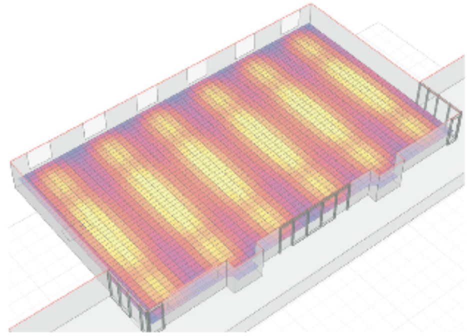
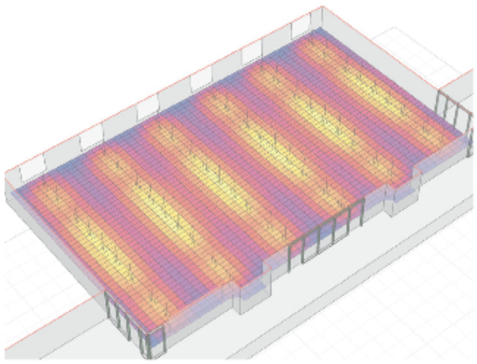
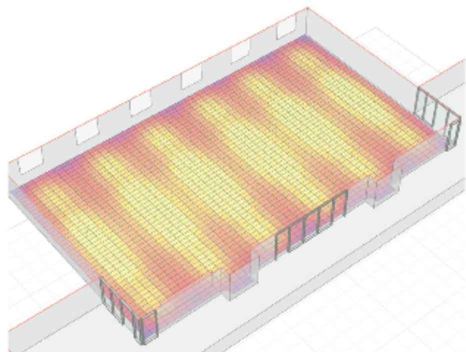
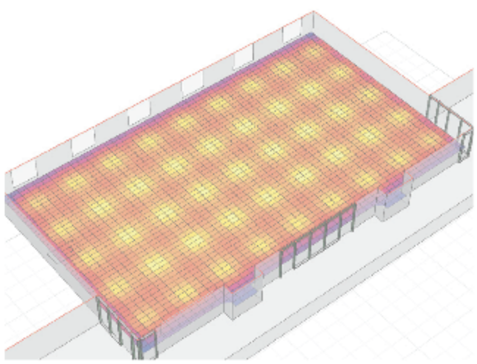
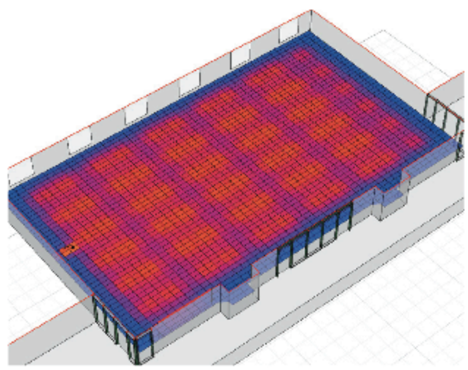
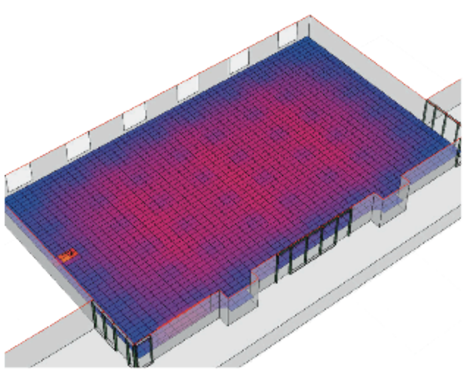

SCHEME.02 //retrofit T-8

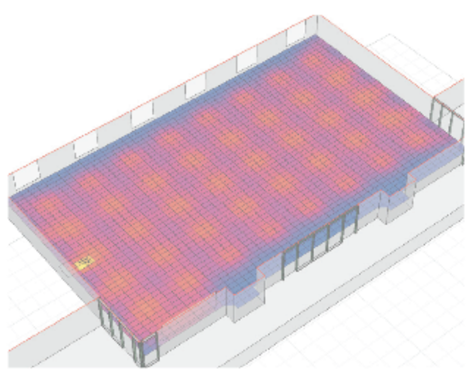

SCHEME.02a //retrofit T-5


SCHEME.02b //retrofit LED


SCHEME.03 //LED


SCHEME.04 //direct-indirect+task


SCHEME.04a //indirect+task


SCHEME.05 //multi scene

Results and Discussion: Illuminance – Wall Plane

Analysis of illuminance among the wall plane is important for presentation purposes during the teaching periods. For teaching spaces, the IESNA RP-1-04 and HI-CHPS EQ.C8.3 specify minimum average illumination levels of at least 30 foot-candles, with an 8:1 or better illuminance uniformity ratio along the wall plane.[75]

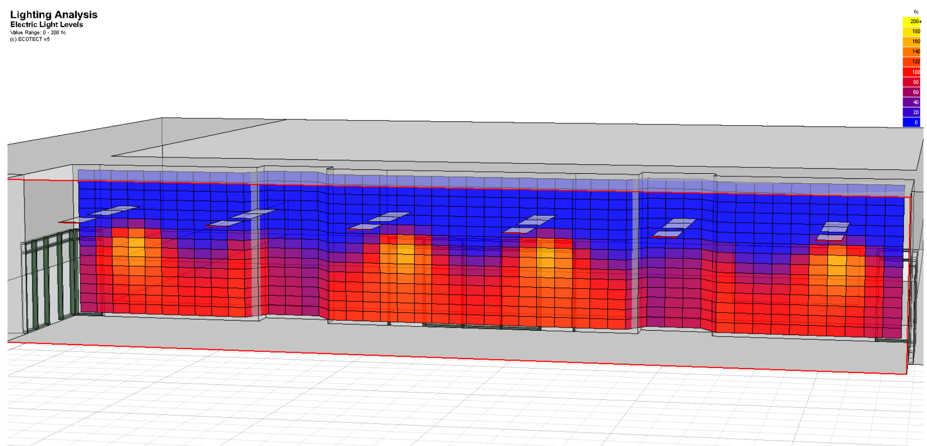


Figure 3.19: Wall Illuminance Analysis - Scheme 1 (Existing)

In all scenarios, average wall plane illuminance fell within illumination standards. Outliers included scheme 1, which showed the lowest average illuminance value of 25.97 foot-candles. The highest average value was 55.7, in scheme 2b. As in the horizontal workplane illuminance analysis, the increased value can be linked to the increased wattage combined with the non-optimal layout.

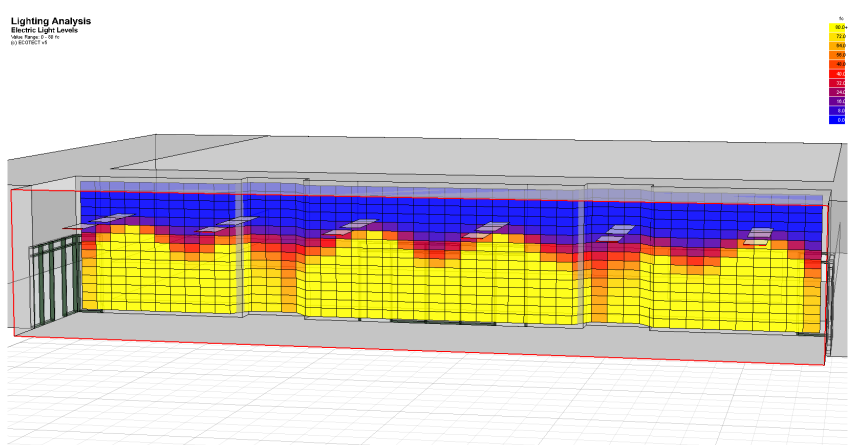


Figure 3.20: Wall Illuminance Analysis - Scheme 2b (LED Relamp)

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[75] *HI-CHPS*, 2012. 92.

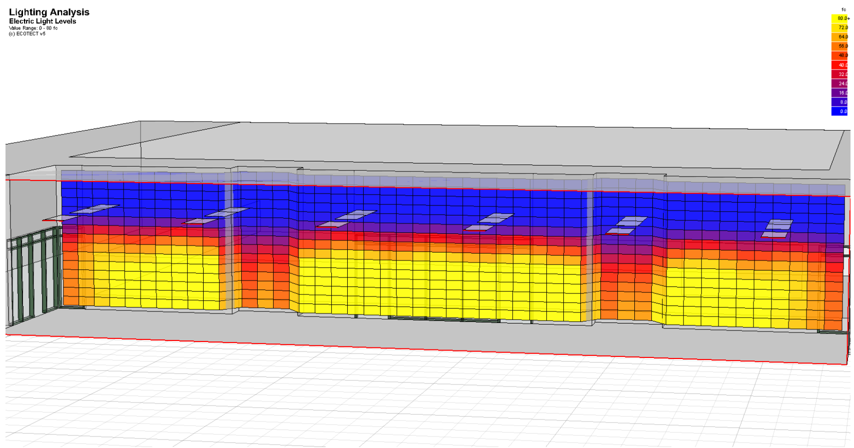


Figure 3.21: Wall Illuminance Analysis - Scheme 3 (LED)

Interestingly, though both schemes 2b and 3 utilized similar 44-watt LED luminaires by CREE, scheme 3 showed a 56% lower average illuminance level. This can be attributed to the difference in both the edge spacing of the luminaires, and the number of luminaires near the wall plane.

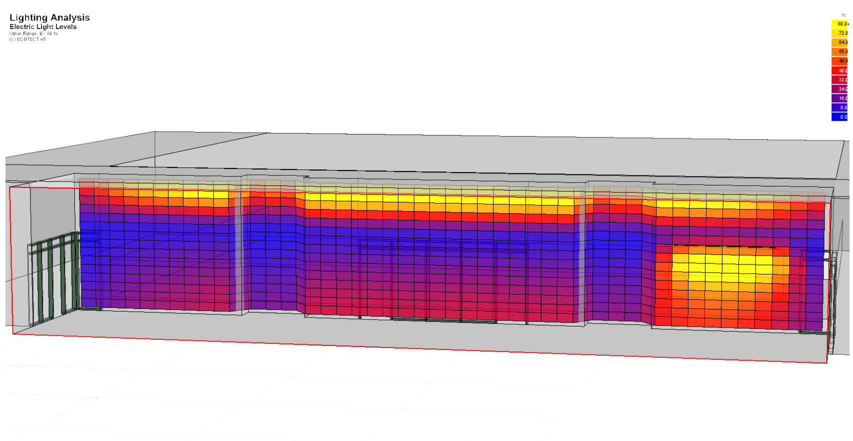


Figure 3.22: Wall Illuminance Analysis - Scheme 4 (Indirect/Direct + Task)

In scheme 4 (shown in Figure 3.22), the illumination on the pin up board ranges between 16-24 foot-candles, making it non-optimal for presentation purposes. Supplemental luminaires were added to raise illumination levels to values to approximately 70 foot-candles. This helps to achieve an increased visual contrast, which will be discussed in greater detail in the following section.

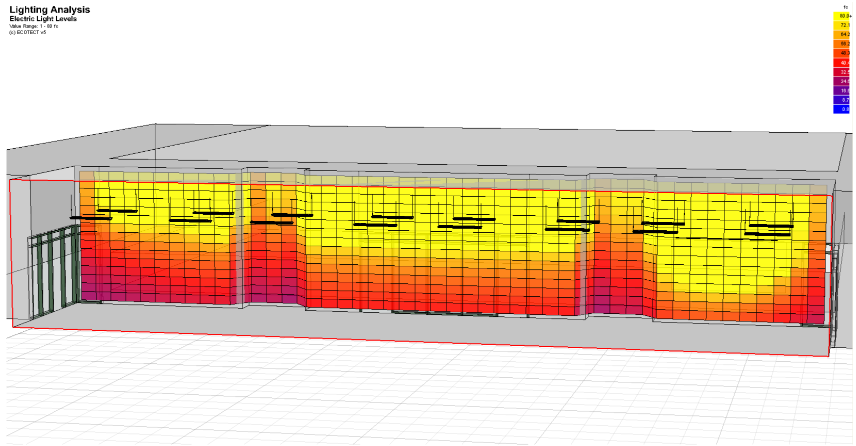


Figure 3.23: Wall Illuminance Analysis - Scheme 4a (Indirect+Task)

Of all the schemes tested, only scheme 4a met both baseline requirements with an average illumination of 31 foot-candles, and an illuminance uniformity ratio of 2:1 along the wall plane.

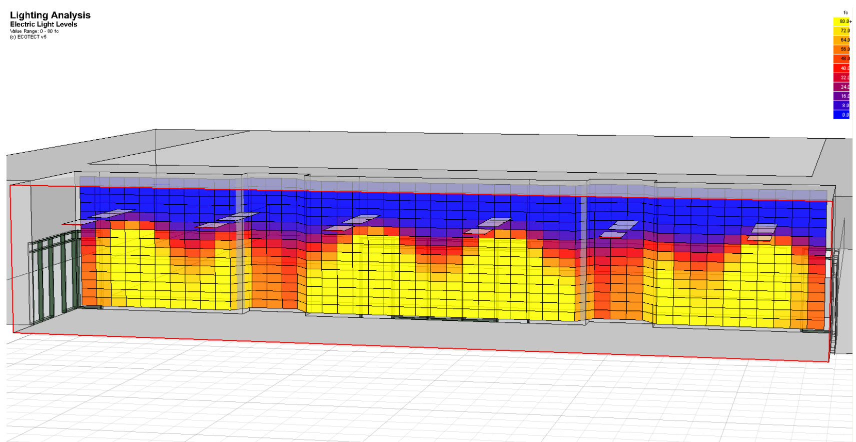


Figure 3.24: Wall Illuminance Analysis - Scheme 2 (Retrofit T-8)

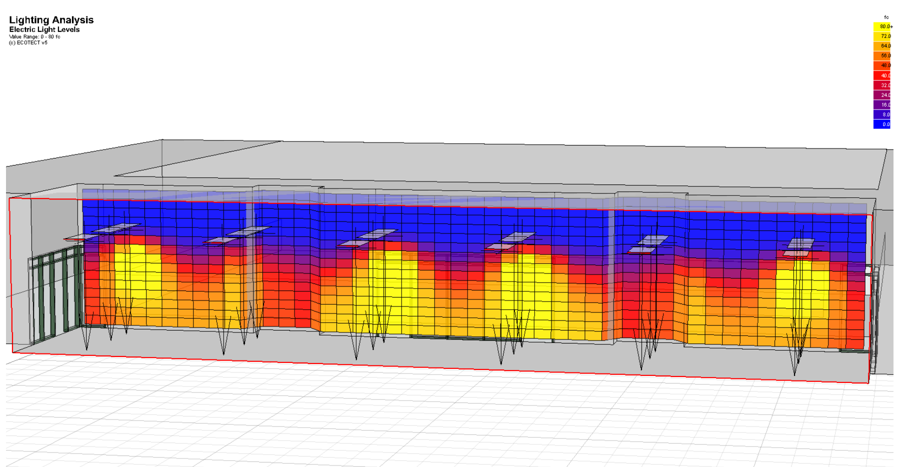


Figure 3.25: Wall Illuminance Analysis - Scheme 2a (Retrofit T-5)

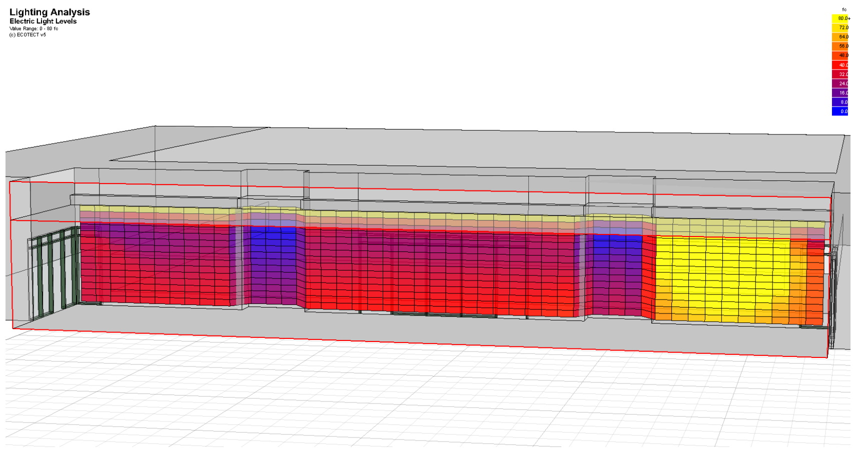


Figure 3.26: Wall Illuminance Analysis - Scheme 5 (Multi-Scene)

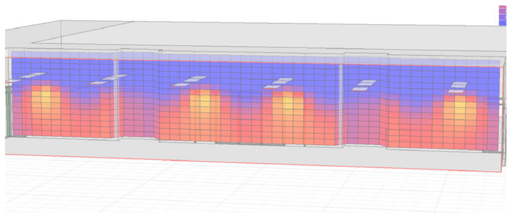
A limiting factor of this particular illuminance uniformity calculation is the consideration of the entire wall surface as the teaching wall. In schemes 3-5, it can be seen that the pin up area, located on the right of the teaching wall indicates uniformity across the whiteboard (area depicted in yellow). As such, these schemes should not be disregarded in terms of providing illuminance uniformity on the wall plane.

Scheme 1 demonstrated an average illuminance of 25.97 foot-candles, which does not meet established guidelines. The remaining schemes fell within criteria, with the exception of schemes 2 and 5, which indicated an average illuminance of 42.79 foot-candles and 49.59 foot-candles, respectively. While these values are marginally higher, they do not represent any negative effects on visual comfort.

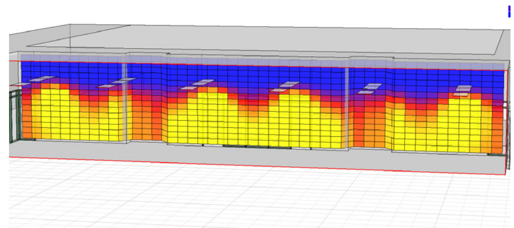
Uniformity ratios for the teaching wall varied significantly among each scheme, showing no correlation with the horizontal workplane illuminance uniformity. Schemes 2a and 5 demonstrated the worst uniformity of all schemes analyzed.

The following page provides a composite of all the images generated during this analysis, allowing for comparison. Images that appear greyed-out do not meet the required baselines, as discussed previously.

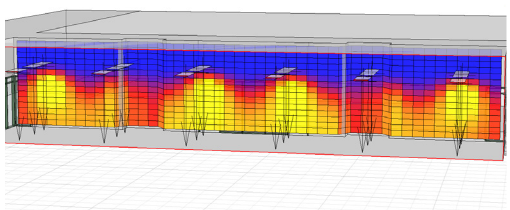
ILLUMINANCE ANALYSIS - WALL



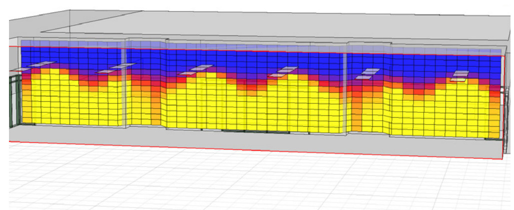
SCHEME.01 //existing



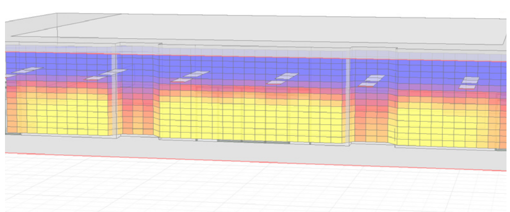
SCHEME.02 //retrofit T-8



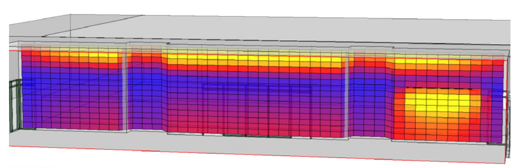
SCHEME.02a //retrofit T-5



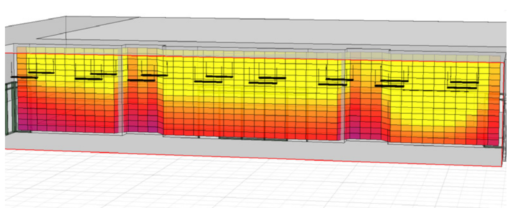
SCHEME.02b //retrofit LED



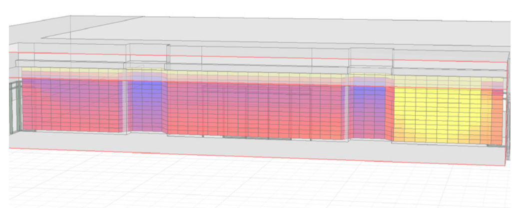
SCHEME.03 //LED



SCHEME.04 //direct-indirect+task



SCHEME.04a //indirect+task



SCHEME.05 //multi scene

Results and Discussion: Luminance - Standing Position

In accordance to RP-1-04 from the IESNA, there are several guidelines regarding luminance levels. One such standard is that the ceiling luminance values should not measure in excess of 850 cd/m^2 (248 fL) at any point. Additionally, contrast ratio should measure no greater than 3:1 between task and adjacent surfaces, and no greater than 10:1 between task and remote surfaces.

In all scenarios, mean ceiling luminance never exceeded 248 fL; this value excludes measurement of luminance values directly from the luminaire. These results imply that all lighting scenarios meet RP-1-04 guidelines from the IESNA for ceiling luminance levels. Additionally, all scenarios met requirements for providing a luminance ratio of at least 3:1 between the pin-up board and adjacent wall surface, with the exception of scheme 1.

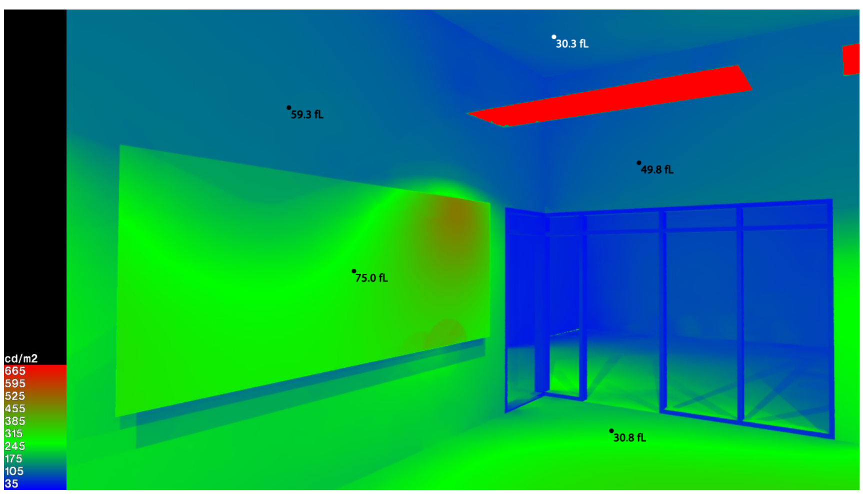


Figure 3.27: Scheme 1 Luminance False-Color Image - Standing (Existing)

In schemes 1-2b, an issue inherent with the existing layout is the hotspot that is generated on the top right corner of the pin up board. This can become visually distracting, but does not appear to cause any visual glare issues, as the contrast ratio is not greater than 3:1.

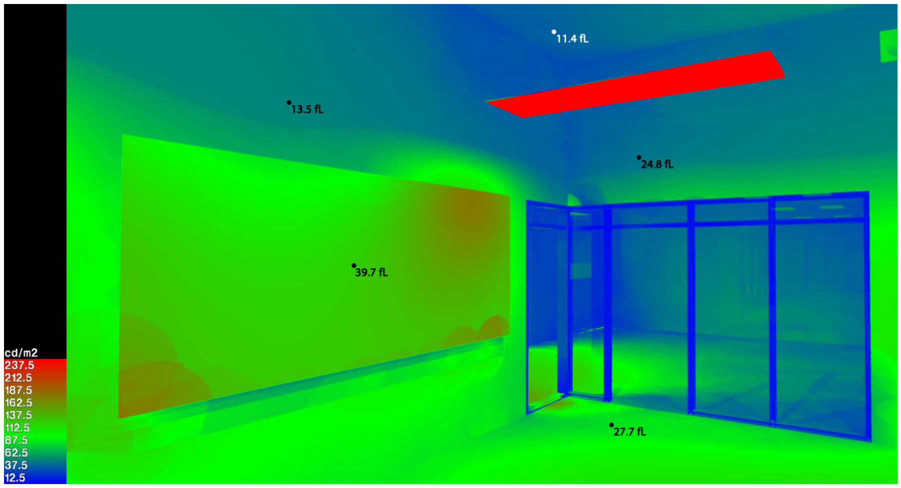


Figure 3.28: Scheme 2 Luminance False-Color Image - Standing (Retrofit T-8)

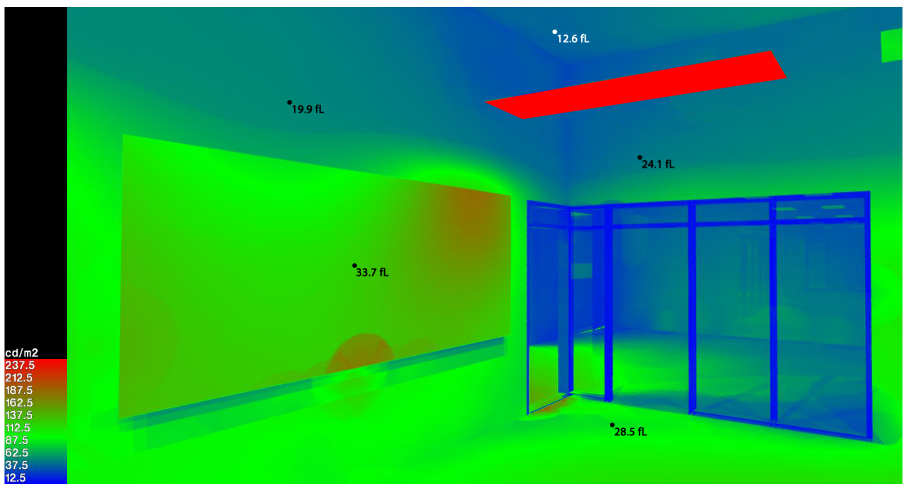


Figure 3.29: Scheme 2a Luminance False-Color Image - Standing (Retrofit T-5)

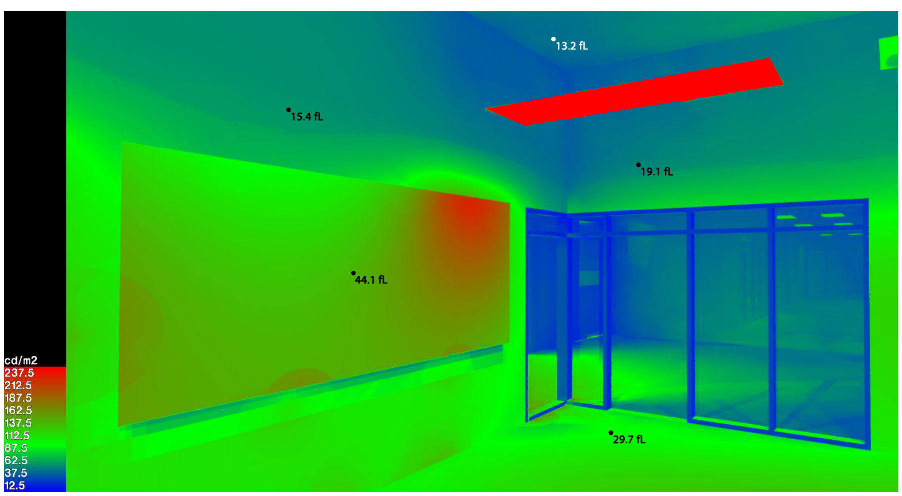


Figure 3.30: Scheme 2b Luminance False-Color Image - Standing (Retrofit LED)

Interestingly, scheme 3 (LED) begins to achieve a degree of uniformity across the pin up board without the use of an additional task lamp mounted above the board. This could be attributed to the spacing of the luminaires, which allowed for a more uniform distribution of light on the vertical plane.

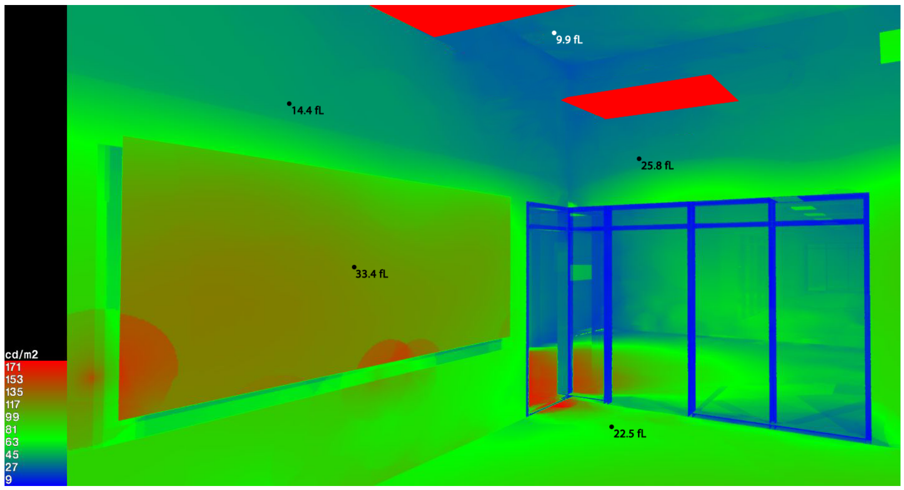


Figure 3.31: Scheme 3 Luminance False-Color Image - Standing (LED)

However, luminance uniformity was noticed to be an issue in a majority of schemes, which is indicated by the distribution pattern of the red region across the pin up board, shown in each of the false-color renderings. With the exception of schemes 4 and 4a, the majority of schemes did not meet the criteria. The success of schemes 4 and 4a is linked to the use of a supplementary task luminaire mounted above the pin up area, which was the added when it was noticed that luminance uniformity on the pin up board was an issue. Earlier schemes that relied primarily on ambient overhead lighting struggled to reach required uniformity across the board's surface. The process of refinement through added task lamps to wash over the board surface alleviated the issue.

Page 66 provides a composite of all the images generated during this analysis to allow for comparison. Images that appear greyed-out do not meet the required baselines, as discussed previously.

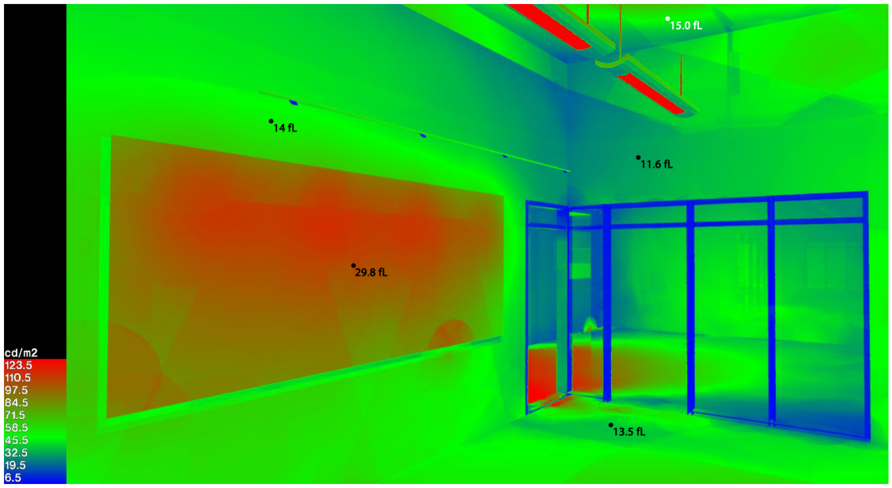


Figure 3.32: Scheme 4 Luminance False-Color Image - Standing (Indirect/Direct+Task)

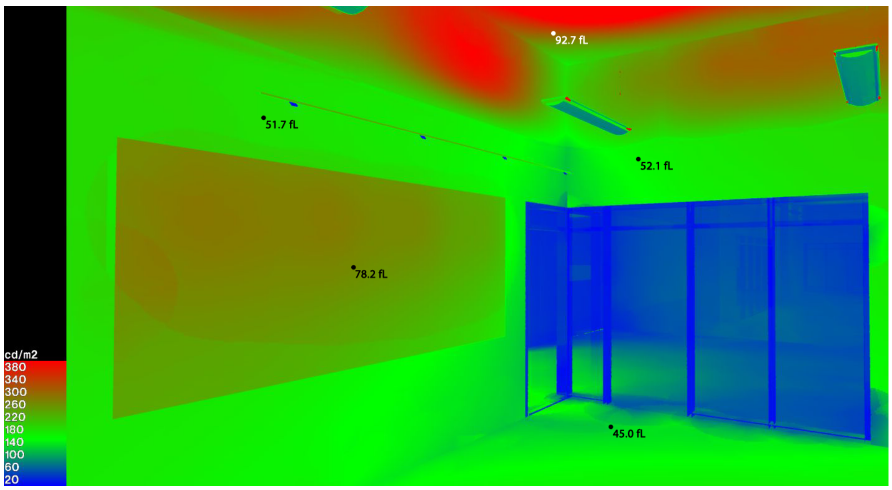


Figure 3.33: Scheme 4a Luminance False-Color Image - Standing (Indirect+task)

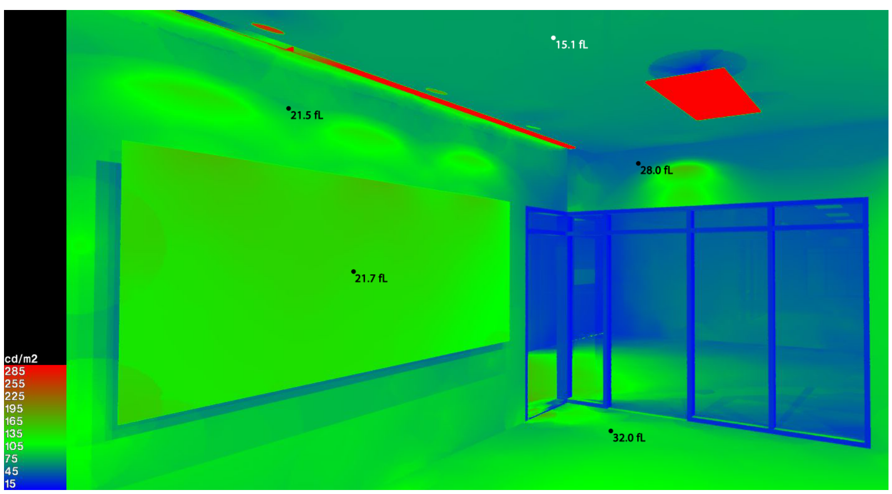
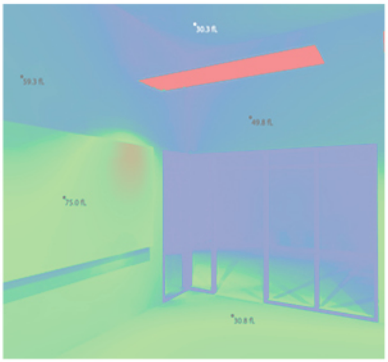
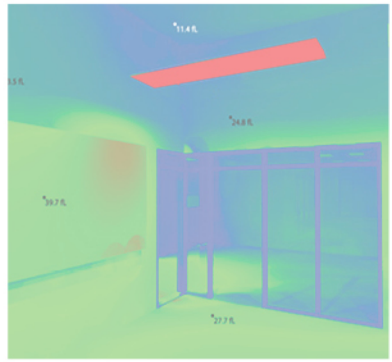


Figure 3.34: Scheme 5 Luminance False-Color Image - Standing (Multi-Scene)

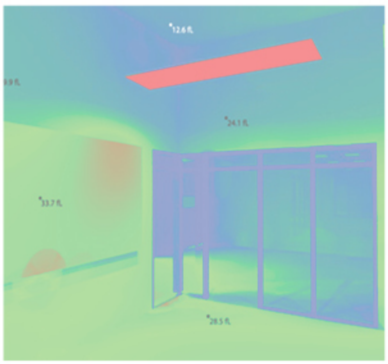
LUMINANCE ANALYSIS - STANDING



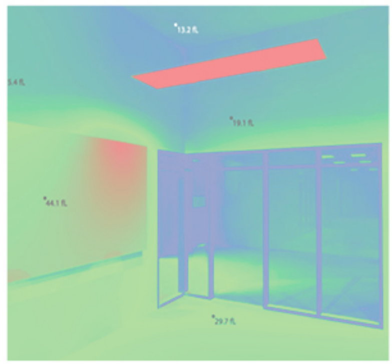
SCHEME.01 //existing



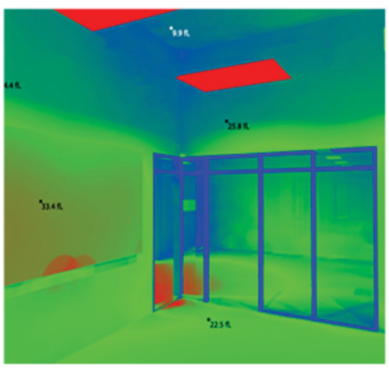
SCHEME.02 //retrofit T-8



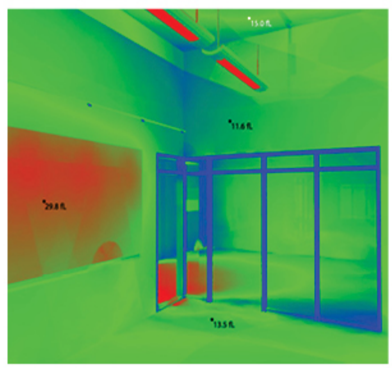
SCHEME.02a //retrofit T-5



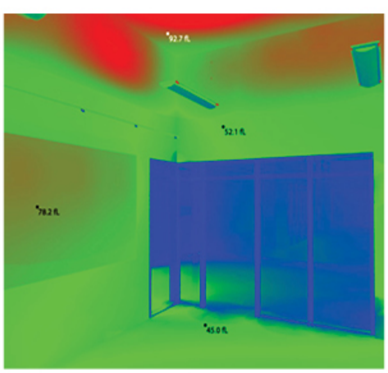
SCHEME.02b //retrofit LED



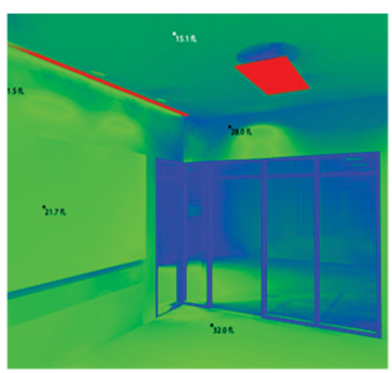
SCHEME.03 //LED



SCHEME.04 //direct-indirect+task



SCHEME.04a //indirect+task



SCHEME.05 //multi scene

Results and Discussion: Luminance – Seated Position

The luminance study for the seated position is similar to the standing position. Both the contrast ratio between the task surface and a remote wall surface are considered, in addition to the contrast ratio between the pin up board and adjacent wall surface as viewed from the seated position. This ensures that the majority of surfaces that a student sees while sitting at their desk are taken into account. Additionally, luminance perception can differ based on viewer perception, so a study from both standing and seated positions was necessary.[76]

As with the luminance study in the standing position, the IESNA RS-1 guidelines are taken into account regarding ceiling illuminance, and contrast ratio. To reiterate, RS-1 guidelines specify that contrast ratios not exceed 10:1 between the task plane and remote wall surfaces. For the seated position, an additional consideration was made to analyze the contrast ratio between the task surface and an adjacent wall plane. In accordance to the IESNA RS-1 guidelines, this contrast ratio should not exceed 3:1.

To calculate the contrast ratio between the task plane and pinup wall, the mean contrast on the pinup wall was divided by the mean contrast on the task plane. For the contrast ratio between adjacent wall and task plane, the mean contrast of the wall to the right of the desk depicted in the false-color image was divided by the mean contrast of the task plane.

[76] *Russell*, 2008. 133.

For all schemes analyzed, both contrast ratio requirements were met. Additionally, mean ceiling luminance values for all schemes did not exceed 248 fL.

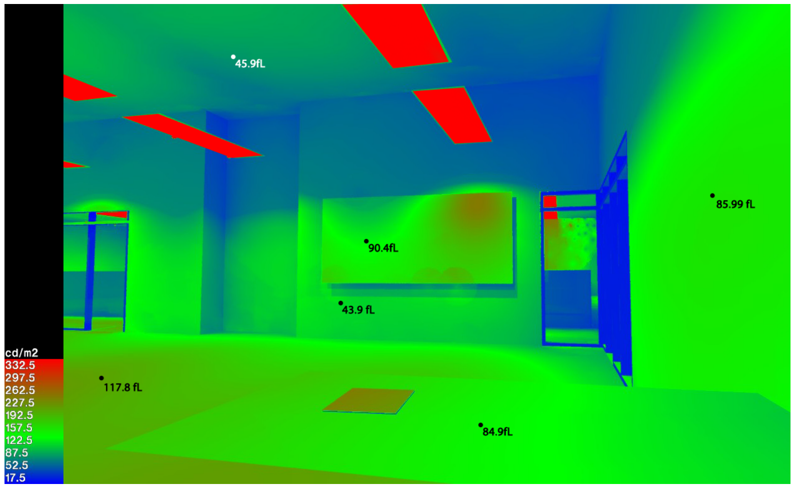


Figure 3.35: Scheme 1 Luminance False-Color Image - Sitting (Existing)

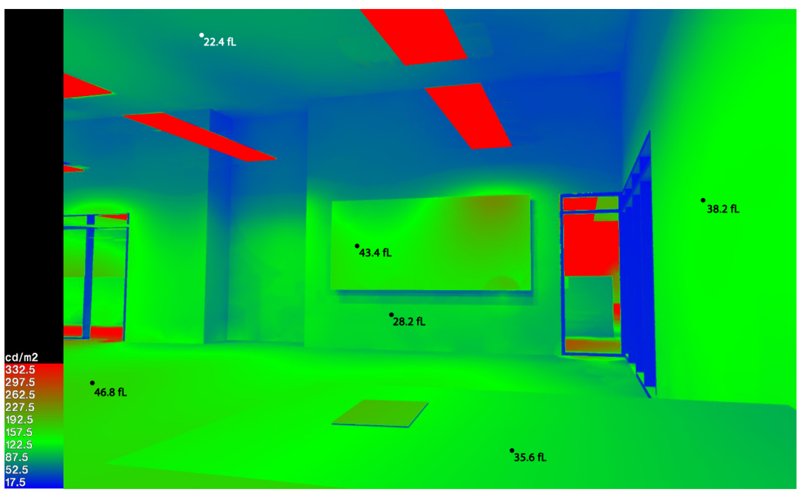


Figure 3.36: Scheme 2 Luminance False-Color Image - Sitting (Retrofit T-8)

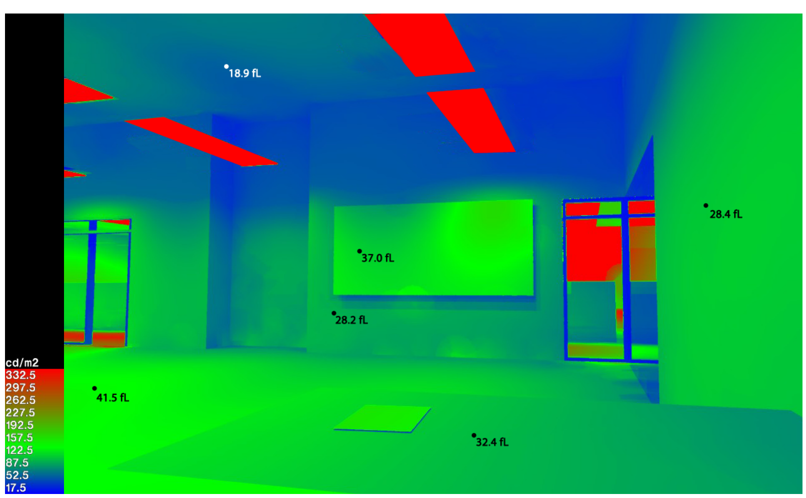


Figure 3.37: Scheme 2a Luminance False-Color Image - Sitting (Retrofit T-5)

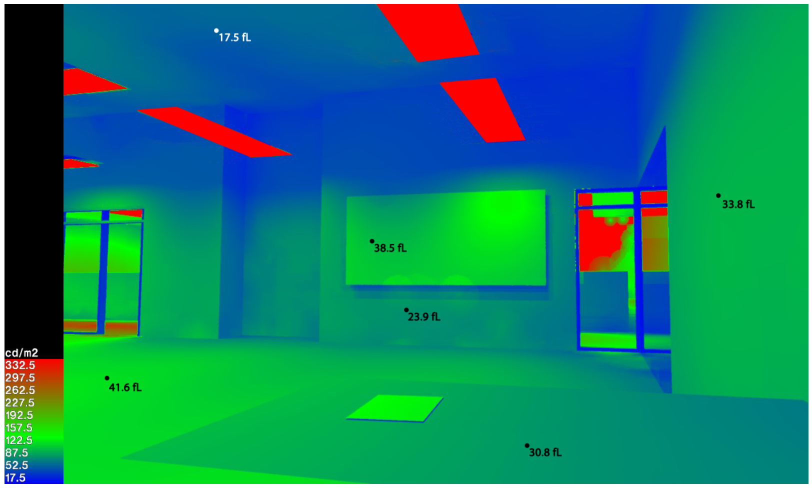


Figure 3.38: Scheme 2b Luminance False-Color Image - Sitting (Retrofit LED)

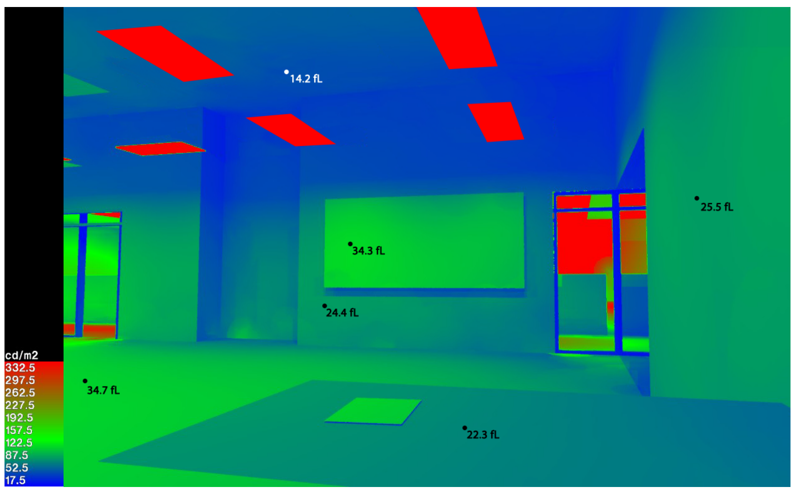


Figure 3.39: Scheme 3 Luminance False-Color Image - Sitting (LED)

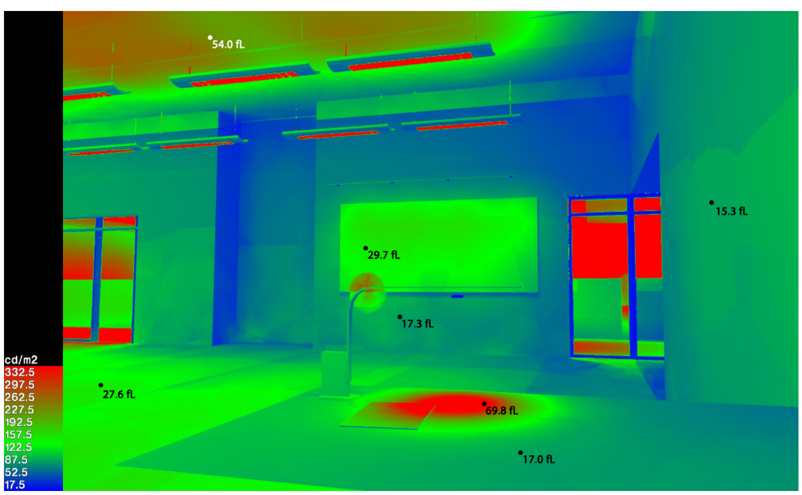


Figure 3.40: Scheme 4 Luminance False-Color Image - Sitting (Indirect/Direct+Task)

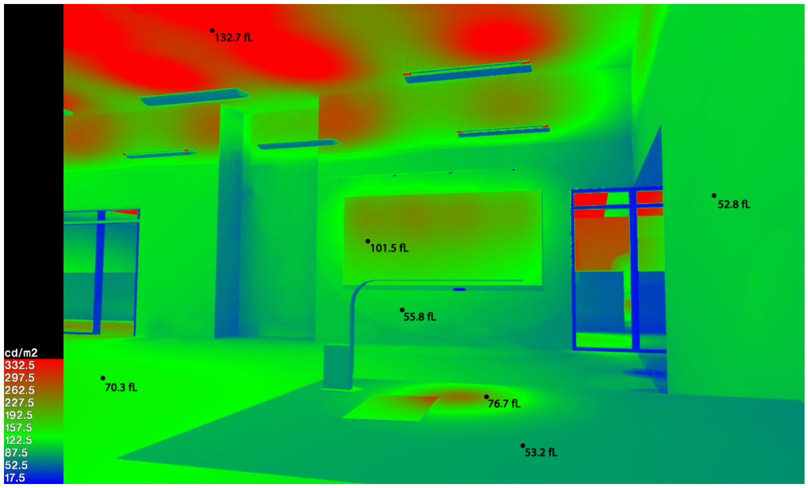


Figure 3.41: Scheme 4a Luminance False-Color Image - Sitting (Indirect+Task)

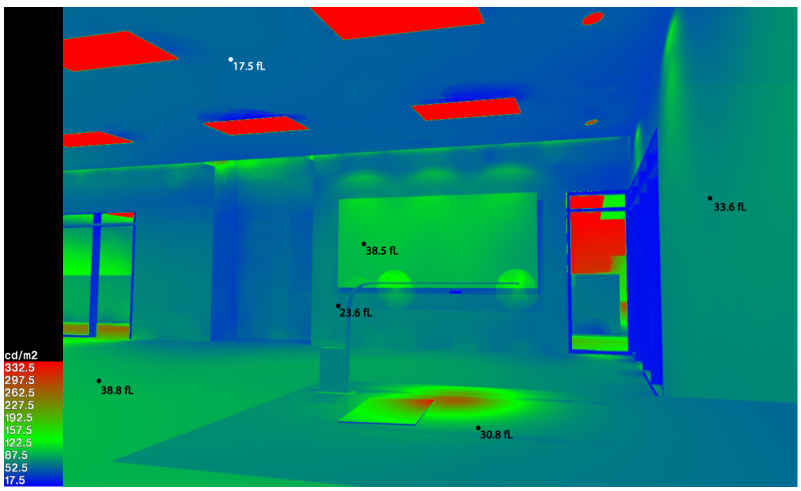
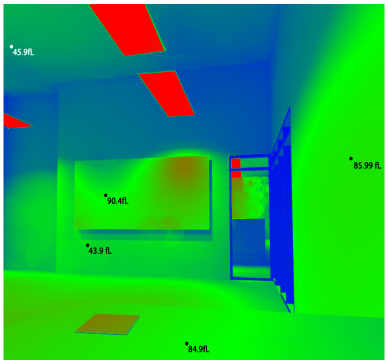


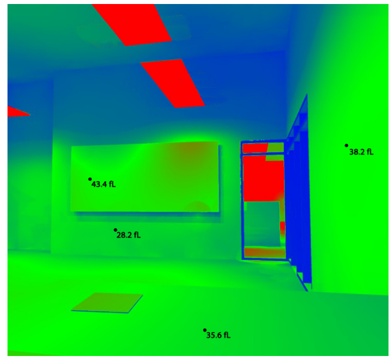
Figure 3.42: Scheme 5 Luminance False-Color Image - Sitting (Multi-Scene)

An observation made from studying the mean luminance levels on the various surfaces of the space revealed that in schemes 1-3, the lowest luminance values within the range were found on floor surfaces. In schemes where an indirect light fixture is used, the lowest luminance values were found on wall surfaces.

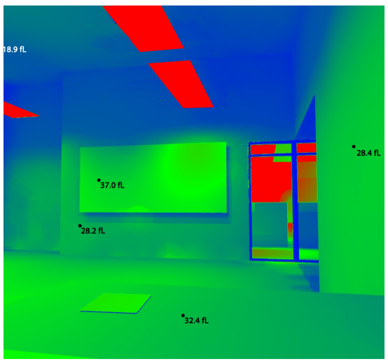
The following page provides a composite of all the images generated during this analysis to allow for comparison. Images that appear greyed-out do not meet the required baselines, as discussed.



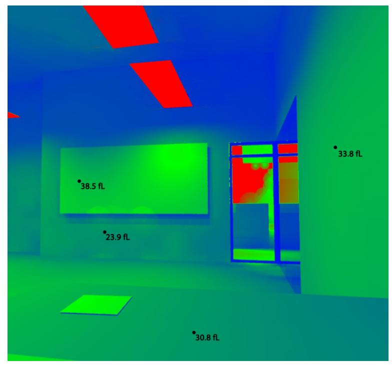
SCHEME.01 //existing



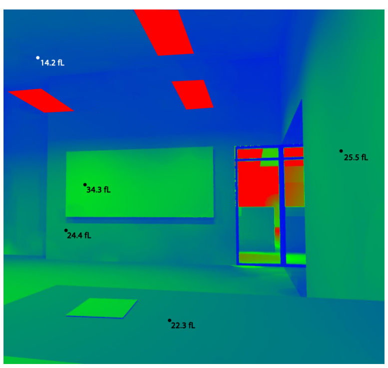
SCHEME.02 //retrofit T-8



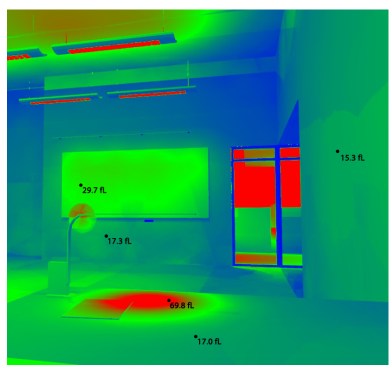
SCHEME.02a //retrofit T-5



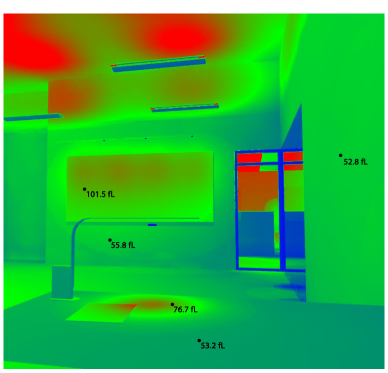
SCHEME.02b //retrofit LED



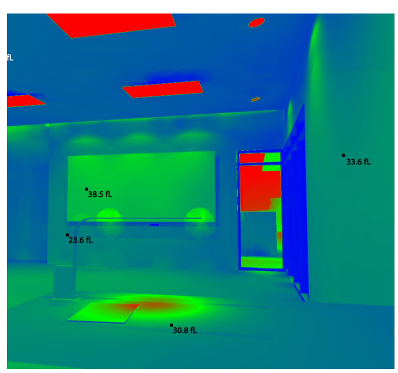
SCHEME.03 //LED



SCHEME.04 //direct-indirect+task



SCHEME.04a //indirect+task



SCHEME.05 //multi scene

LUMINANCE ANALYSIS - SEATED

Results and Discussion: Cost Analysis

The following table provides an overview for the initial cost, maintenance, costs, and savings for each scheme:

Scheme No.	Initial Cost	Annual M&O Costs	M&O Savings Over Original
1 (Existing)	-	$4,784.08	-
2 (Retrofit T-8)	$8,972.10	$2,529.29	$2,254.79
2a (Retrofit T-5)	$14,265.72	$3,041.71	$1,742.37
2b (Retrofit LED)	$7,829.46	$2,178.32	$2,605.76
3 (LED)	$16,243.11	$1,815.26	$2,968.82
4 (Ind/Dir+Task)	$61,854.42	$2,581.00	$2,203.08
4a (Ind+Task)	$35,875.50	$1,672.62	$3,111.46
5 (Multi-scene)	$30,661.41	$2,126.72	$2,657.36

Table 3.2: Overview of cost analysis for different schemes

It was found that the replacement of the existing lighting with any proposed scheme would result in annual maintenance and operating costs savings of at least 35% over the existing. Of the schemes, Scheme 4a (Indirect+Task) provides the greatest maintenance and operation cost savings over the existing lighting. However, it is the most expensive of all the relamping solutions analyzed here, at $14,200. Of the retrofit solutions, Scheme 2b (Retrofit LED) represents the best cost-benefit value of all proposed schemes. It offers the lowest implementation investment of approximately $7,800 for a proposed savings of $2,605 per year per classroom over the existing lighting.

Based on initial implementation costs alone, Scheme 4 (Indirect/Direct+Task) was the most expensive, costing approximately $62,000 to install. The increased cost is a result of the high per-unit price of the Ledalite Sona luminaire, at approximately $670 per unit. In comparison, the Arcos Perf II luminaire used in Scheme 4a (Indirect+Task) is priced at approximately $400 per unit. The relatively high initial investment of these architectural indirect-direct luminaires potentially becomes a prohibiting factor for education administrators seeking to improve lighting conditions for students.

04 **Conclusion**

Simulation Study Conclusions

From a performance standpoint, Scheme 4, which utilizes a combination of indirect-direct luminaires and desk-mounted task lamps, meets all evaluative baselines and goals. Scheme 4 shows most optimal illuminance uniformity on both the horizontal and wall workplanes while meeting the minimum average of 30 maintained foot-candles. Furthermore, it shows optimal contrast ratios both in the seated and standing positions. From an economic standpoint, scheme 4 does not offer the most cost-effective or economic solution. As stated in the cost analysis, scheme 2b presents the most cost-effective solution of all the schemes, providing a low implementation costs while providing potential savings of up to $2,605 annually over the existing lighting.

Additional conclusions can be made in regards to the initial comparison of LEED, HI-CHPS, and BREEAM introduced in chapter 2. In order to provide clarity, these conclusions will be categorized into three main subsections that address green building analysis systems, task performance, and the results of the experimentation simultaneously.

Illuminance Levels

As stated in the literature review, the IESNA provides standards for illuminance levels for educational facilities of between 30-50 average foot-candles on the horizontal workplane. All of the schemes designed and tested here were designed with the IESNA standards taken into consideration. As a result, all schemes provide an average illuminance of at least 30 foot-candles on both the horizontal and vertical workplanes. In the literature review, it was noted that LEED guidelines lack a reference towards minimum illuminance levels. As such, LEED guidelines should be revised to add guidelines for minimum illuminance levels on the horizontal workplane to match those guidelines HI-CHPS and BREEAM to ensure that students receive proper minimum illumination for tasks in the classroom.

In reference to a study by Goven et. al outlined in chapter 2, there are benefits of increasing illuminance levels and increased test scores in school children. However, raising illuminance levels to upper limits for an entire room is not an economically sound solution and leads to over-illumination. Rather, providing task lighting at desks allows for illumination levels to be raised only where necessary. This allows for the ambient lighting levels to remain lower, providing energy savings. A proposed guideline revision could be made to enforce the use of task lamps in classrooms with a necessity for higher illumination levels, due to the added flexibility and potential energy savings they offer.

Illuminance Uniformity

As it currently stands, neither the IESNA nor BREEAM, LEED, and HI-CHPS have a specified illuminance uniformity ratio specified for the horizontal workplane, making it difficult for lighting designers and engineers to have a numerical basis of which to base illuminance uniformity on the horizontal workplane. From the analysis findings and calculation of minimum-to-average uniformity ratio, it can be seen that when an acceptable level of uniformity is achieved on the analysis grid, the calculation of minimum-to-average uniformity levels is at least 4:1 or better. Given these findings, 4:1 minimum-to-average uniformity ratio should be adopted as an acceptable standard of uniformity for open plan classrooms.

The noticeable benefits of illuminance uniformity as outlined in the literature review include minimization of visual distraction and VDT glare in the workplace, which indirectly affects task performance through comfort factors and task visibility. From the experimentation process, it became apparent that illuminance uniformity on the horizontal workplane was an issue with the existing lighting in the studio classroom. For retrofit applications where reconfiguration of luminaire spacing is not possible due to budget or other considerations, the ability to provide uniform lighting can be problematic. For these situations, the best practice would be alleviating the non-uniformity scenario by introducing selecting luminaires with different photometric distributions. User controls and task lamps could be added to detract the user experience from the poor uniformity.

The lighting uniformity analysis of the existing studio classroom (scheme 1) exemplifies the need for LEED, HI-CHPS, and BREEAM guidelines to incorporate an illuminance uniformity ratio guideline. According to research by Slater and Boyce referenced in the literature review, illuminance uniformity was considered unacceptable when it reached 8:1 or greater. From the uniformity analysis simulation performed for the given illumination levels, mean illuminance levels did not appear to exhibit a uniform pattern until a ratio of 4:1 or greater was reached.

Only BREEAM provides a guideline for illuminance uniformity of 0.6 or better. To ensure that classroom illuminance meets a standard of uniformity that does not affect student visual comfort, LEED and HI-CHPS should include guidelines to specify illuminance uniformity on the workplane of 4:1 or greater. Likewise, illuminance uniformity ratios on the vertical workplane should be at minimum of 5:1 or greater, as found from the simulation study.

Luminance and Visual Contrast

As stated in the literature review, luminance and visual contrast is critical when dealing with presentation and A/V tasks in the classroom. Because a contrast ratio between 2:1 to 5:1 is recommended, the degree of contrast between the presentation object and surrounding object is not as critical as the pattern of luminance. The pattern of luminance is important in providing visual contrast without inducing visual fatigue. Through the simulation of the schemes, Radiance allowed for a visual representation of luminance data through false-color imagery. From this, the only schemes that provided a luminance pattern that was devoid of hotspots and dark areas were the schemes that utilized an additional task lamp mounted above the presentation area. In relation to BREEAM, LEED, and HI-CHPS guidelines, a proposed guideline revision would be made to require an additional track luminaire to be mounted over the presentation area.

The following outlines a summary of the proposed changes to be made to the existing green building analysis guidelines, as described in previous subsections:

- The existing basis of IESNA and CIBSE guidelines for illuminance levels as used by HI-CHPS (IEQ.C8.4/8.5) and BREEAM (HEA5) is a good method of ensuring that students have an adequate amount of illuminance to perform school tasks.
- LEED should revise the Schools 3.0 guidelines to include provisions for defining illuminance levels on the horizontal and vertical task planes
- HI-CHPS, LEED, and BREEAM should define a minimum-to-average uniformity ratio of 4:1 on the horizontal workplane, and 5:1 on the vertical plane.
- HI-CHPS, LEED, and BREEAM need to specify the use of a light over the pin-up gallery space/teaching wall to ensure that luminance patterns and contrast are ideal.
- The importance of user controllable switching is important in user comfort and productivity, as indicated by Slater and Boyce. Therefore, HI-CHPS, LEED, and BREEAM should award more credits to provisions for user switchable lighting. Currently, BREEAM and LEED offer 1 credit for addition of user controls as specified in BREEAM HEA6 and LEED IEQ 6.1.

Reflection of the Study

Reflecting upon the completed study, there are aspects in which this study could have been improved to provide increased accuracy and relevancy of the results and outcomes. In particular:

- Having a more complete technical understanding of Desktop Radiance would allow for increased accuracy and aesthetically pleasing renderings with applied materials on the floor, walls, desk, and ceiling planes beyond generic clay materials with estimated reflectance and glare data. This would result more accurate analytical images that provided better context of objects within the visual field.
- Further integration of an annual daylighting study and how photo sensor switching can affect energy consumption and operation of each lighting scheme.

- Gain a better understanding of usage patterns through observation of the space during typical teaching hours could reveal better development of lighting schemes to meet ideal needs. Going beyond assumptions based on personal experience, this would inform where the primary areas of activity lie, and how the space is used.
- Surveying students and faculty to acquire opinions on preferred lighting schemes and lighting conditions from the study would factor user preference into the findings of these studies.

Suggestions for Future Research

An alternative direction that this research could be taken with further development is to act as a basis for pedagogical applications. The extensive lighting studies and clarity of organization of that information can provide can be utilized as the framework to derive an educational curriculum for architecture students to learn more about nuances of light within the bounds of architecture.

Appendix

Lithonia ES8R Luminaire Cutsheet: Used in Scheme 2

LITHONIA LIGHTING®

Catalog Number
Notes
Type

FEATURES & SPECIFICATIONS

INTENDED USE — The ES8R is an ideal solution for relighting a parabolic installation when a one-for-one upgrade is desired. ES8R is designed for installation into host **2'x4' parabolic fixtures that are a minimum of 4-3/8"** deep. ES8R is not specifically designed for lensed troffer upgrades or lensed troffer with parabolic renovator kit installations. Ideal for retail, educational, commercial and other general lighting applications. ES8R delivers more balanced light levels vertically and horizontally while eliminating the "cave effect" produced by traditional parabolic fixtures. ES8R provides substantial energy savings of up to 45% compared to a three-lamp T8 electronic ballast system and up to 56% savings compared to a three-lamp T12 ES magnetic system.

CONSTRUCTION — The ES8R assembly consists of six primary components plus hardware.

Universal end brackets containing the prewired ballast and sockets are constructed of 20-gauge painted steel and are secured to host fixture with TEK screws. A splice box is provided to enclose electrical connections and a ballast disconnect plug is installed standard.

The reflector system is constructed from highly reflective white paint and easily attaches to the end brackets with 1/4 turn fasteners.

Robust design, precision-tooling and automated assembly combine to create the industry's strongest louver.

Finish: Louver assembly painted after fabrication with low gloss, high reflectivity polyester powder coat. Reflectors finished in highly reflective computer controlled gloss white paint.

OPTICS — Mechanical shielding is provided with angled length blades and linear faceted cross baffles. Contoured housing efficiently directs light downward. Lamp cut-outs maximize shielding while minimizing overall assembly depth to provide consistent performance in any host fixture application. Vertical light levels are improved providing a balanced amount of light across all surfaces.

ELECTRICAL — Standard ballast is high-efficiency, CEE (Consortium for Energy Efficiency) qualified, instant-start, <10% THD, universal voltage and sound rated A. Suggested lamps are high lumen, long-life Super T8 lamps which contribute to maximizing system performance. Optional program start and step-dimming ballasts are available as well as several ballast factor options.

INSTALLATION — Louver assembly hinges from either side for access to lamps. For ballast access, continue process by removing 1/4 turn fasteners and reflectors.

LISTING — UL Listed/C-UL Classified. Labeled for use in both static and air-handling fixtures. Does not impact existing UL listing. NYC approved (#49192).

WARRANTY — Fixture guaranteed for one year against mechanical defects in manufacture. Lamp and ballast system warranty for 36 months for lamp, 60 months for ballast by lamp and ballast manufacturer.

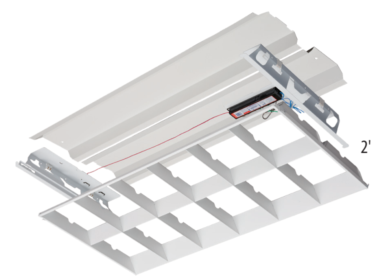
Protected by US Patent Nos. 6,210,025; 6,231,213. Additional patents pending.

Specifications subject to change without notice.

es8™ RELIGHT

Relight Assembly

ES8R



2' X 4' Relight Assembly
2 Lamp T8

Specifications

Intended to be installed in any existing parabolic recessed fixture:

Weight: 21 lbs.

ORDERING INFORMATION For shortest lead times, configure products using **bolded options**.

Example: 2ES8R 232 BILP

2ES8R	232			
Series	**Number of lamps/ wattage**	**Voltage**	**Ballast**	**Options**
2ES8R	**232** 2-lamp, 32W T8 (48")[1]	(blank) MVOLT[2] 347 347V	**BILP** IS, high efficiency, .78 bf (low) **BINP** IS, high efficiency, .88 bf (normal) BIHP IS, high efficiency, 1.20 bf (high)[3] BSNP PS, step-dimming, high effiency, .88 bf (normal)[4]	**JP18** Job pack 18

Accessories: *Order as separate catalog number.*	
RRC4	Side reveal cover (pair), available in sets of five (pairs) or 25 (pairs)

Notes

1 Lamps not included. Must be ordered separately.
2 MVOLT standard for 120V-277V applications.
3 Not available in high-efficiency 347V.
4 Not available in 347V.

Lithonia 2RT5 Luminaire Cutsheet: Used in Scheme 2a

LITHONIA LIGHTING®

Catalog Number	
Notes	
Type	

FEATURES & SPECIFICATIONS

INTENDED USE — RT5 is designed for applications that require the extremely energy efficient delivery of comfortable volumetric light from a lay-in fixture that is appealing and shallow in depth. Ideal for offices, schools, hospitals, retail and numerous other commercial applications. **Certain airborne contaminants can diminish integrity of acrylic. Click here for Acrylic Environmental Compatibility table for suitable uses.**

CONSTRUCTION — Impact modified acrylic prismatic refractor with polymer light-diffusing film.

Rugged, one-piece, cold-rolled steel reflector with embossed facets. Polyester powder paint after fabrication.

Rigid structure with ballast box and endplates with integral T-bar clips.

Fixtures may be mounted end-to-end.

OPTICS — Delivers volumetric lighting by filling the entire volume of space with light, delivering the ideal amount to walls, cubicles, work surfaces and people.

Luminous characteristics are carefully managed at high angles, providing just enough intensity to deliver the volumetric effect.

Regressed, two-piece refractive system obscures and softens the lamp and smoothly washes the reflector with light.

Linear faceted reflector softens and distributes light into the space and minimizes the luminance ratio between the fixture and the ceiling.

Mechanical cut-off across the reflector and fresnel refraction along the refractor provide high angle shielding and a quiet ceiling.

Sloped endplates provide a balanced fixture to ceiling ratio while enhancing the perception of fixture depth.

ELECTRICAL — Highly efficient program-start electronic ballasts, Class P, thermally protected, resetting, HPF, non-PCB, UL Listed, CSA Certified, sound rated A. Your choice of Premium or Premium XP T5 lamp with enhanced phosphors and 85 CRI. Ballast/lamp efficacy up to 100+ LPW. Lamp is TCLP compliant.

0.90 or 0.95 ballast factor standard for typical applications. 1.15 ballast factor or F54T5HO lamping available for higher ceiling height applications.

Step-level dimming option allows system to be switched to 50% power for compliance with common energy codes while maintaining fixture appearance.

S5 option available for use with SIMPLY5™ Lighting Intelligence system with multi-level dimming. See SYNERGY® Lighting Controls specification sheets for more information. Ballast Disconnect provided standard where required to comply with U.S. and Canadian electrical codes.

INSTALLATION — Side mounted ballast tray accessed by removing adjacent ceiling tile. Ballast tray may be removed from fixture during service.

Lamps accessed by squeezing refractor to release from retention tabs.

LISTING — UL Listed (standard). Optional: Canada CSA or cUL. Mexico NOM.

WARRANTY — Fixture guaranteed for one year against mechanical defects in manufacture. Lamp and ballast system warranty (24 months for lamp, 60 months for ballast) by lamp and ballast manufacturer.

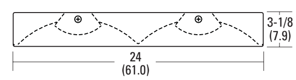
2RT5

2'X 4'
2 Lamps
Premier or Premier XP T5

SIMPLY5™ LIGHTING INTELLIGENCE

Specifications

Length:	48 (121.8)
Width:	24 (61.0)
Depth:	3-1/8 (7.9)



All dimensions are inches (centimeters) unless otherwise specified.

Protected by one or more of US Patents Nos. 7,229,192; D541,467; D541,468; D544,633; D544,634; D544,992; D544,933 and additional patent pending.

Specifications subject to change without notice.

ORDERING INFORMATION For shortest lead times, configure products using **bolded options**.

Example: 2RT5 28T5 MVOLT GEB95 LPM835P

2RT5					
Series	**Lamp type**	**Voltage**	**Ballast**	Lamp[7]	**Options**
2RT5 Recessed T5	**28T5** 28W T5 (46") 54T5HO 54W T5 (46")[1]	**MVOLT**[2] 347[3]	**GEB95** .95 ballast factor **GEB95S** .95 ballast factor, step dimming[4] GEB115 1.15 ballast factor GEB115S 1.15 ballast factor, step dimming GEB10PS 1.0 ballast factor, program start[5] S5 .95 ballast factor SIMPLY5™ system[6] GEB80 .80 ballast factor[1] GEB80S .80 ballast factor, step dimming[1] GEB90 .90 ballast factor GEB90S .90 ballast factor, step dimming GEB10PS 1.0 ballast factor, program start[4]	**LPM835P** Premier 3500° K 28W lamp[8] LPM830P Premier 3000° K 28W lamp[8] LPM841P Premier 4100° K 28W lamp[8] L835XP Premier XP 3500° K 28W lamp[8] L830XP Premier XP 3000° K 28W lamp[8] L841XP Premier XP 4100° K 28W lamp[8] LP835 3500° K 54W lamp LP830 3000° K 54W lamp LP841 4100° K 54W lamp	GLR Internal fast-blow fuse[9] PWS1836 6' prewire, 3/8" diameter, 18-gauge, 3-wire (n/a with step dimming)[10] PWS1846 6' prewire, 3/8" diameter, 18-gauge, 4-wire[11] **EL14** Emergency battery pack[12] EL65 Emergency battery pack[12] HW Hardware for SIMPL5 system; replaces RELOC® CSA Listed and labeled to comply with Canadian standards BDP Ballast disconnect plug (meets codes that require in-fixture disconnect)

Notes

1 For T5HO applications, use GEB10PS, GEB80 or GEB80S ballast.
2 MVOLT (120-277 volts), 50-60HZ.
3 For 347V, use GEB95S or GEB10PS.
4 Only option for 347V.
5 Not available with 28T5.
6 SIMPLY5 includes 13' S5 SSC RELOC® wiring system, specify voltage unless HW (hardwire) or PWS is ordered.
7 Required. All fixtures shipped with lamps installed.
8 28T5 lamp type only.
9 Must specify voltage, 120 or 277.
10 For use with standard ballast.
11 For use with step dimming ballast.
12 See PS1400QD spec sheet for EL lumen output information.

Lithonia 2RT5 Luminaire Cutsheet: Used in Schemes 2b,3,5

CR24™

2'x4' Architectural LED Troffer

Product Description

The CR24™ architectural LED troffer delivers up to 5000 lumens of exceptional 90+ CRI light while achieving 90-110 lumens per watt. This breakthrough performance is achieved by combining the high efficacy and high-quality light of Cree TrueWhite® Technology with a unique thermal management approach. The CR24 is available in neutral or cool color temperatures and has both 0-10V and step dimming options. Its compact, lightweight design easily accommodates recessed, surface mount, or suspended installations, making the CR24 perfect for use in commercial new construction or retrofit applications.

Performance Summary

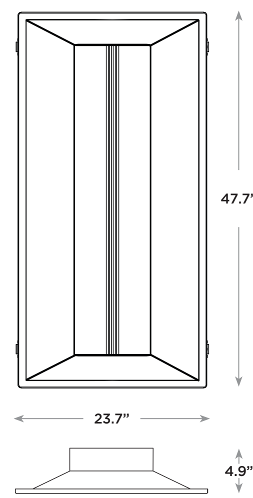
Utilizes Cree TrueWhite® Technology
Active Color Management
Room-Side Heat Sink
Made in America
Efficacy: 90-110 LPW
Delivered Light Output: 2200, 4000, 5000 lumens
Input Power: 22-50 watts
CRI: 90
CCT: 3500K, 4000K
Input Voltage: 120-277 VAC
Warranty: 5 years standard or 7 years with High Efficacy (HE) option
Lifetime: Designed to last 50,000 hours standard or 75,000 hours with HE option
Dimming: Step Level to 50%, 0-10V Dimming to 5%†
Mounting: Recessed
Dimensions: L 47.7" x W 23.7" x H 4.9"
Weight: max 20lbs.

Housings & Accessories

Reference Housing & Accessory documents for more details.

Accessories	
SMK-CR24** Surface Mount Kit	**CPLCR*** Chicago Plenum Field Kit
DGA24-WHT* Drywall Grid Adaptor-White	**CPLCR-EM*** Chicago Plenum Field Kit-Emergency
EJBCR-5PK* Expanded size junction box for through wiring (5 pack)	

CR24



NOTE: Use of Expanded Junction Box will expand the depth to 6.67" and Emergency Backup will expand the depth to 6.30".

Ordering Information

Example: CR24-40L-35K-S

CR24					
Product	**Lumen Output**	**Color Temperature**	**Voltage**	**Control**	**Options**
CR24	**22L** 22W 2200 lumens - 100 LPW **40L** 44W 4000 lumens - 90 LPW **40L HE***** 36W 4000 lumens - 110 LPW (35K) 38W 4000 lumens - 105 LPW (40K) **50L** 50W 5000 lumens - 100 LPW	**35K** 3500 Kelvin **40K** 4000 Kelvin	**Blank** 120-277 Volt (Standard)	**S** Step Dimming to 50% **10V** 0-10V Dimming to 5%	**EB14**** Emergency Backup-1400 lumens

* Target Availability Early 2012. **Target Availability Mid 2012. ***3500K HE model is 36W (110 LPW), 4000K HE model is 38W (105 LPW).
† Reference CreeLEDLighting.com for recommended dimming control options.

CREE TRUE WHITE TECHNOLOGY

c UL US LISTED

CreeLEDLighting.com T (800) 236-6800 F (262) 504-5415

CREE®

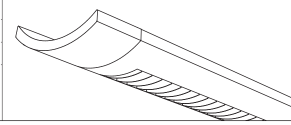
Ledalite Sona Luminaire Cutsheet: Used in Scheme 4

Sona™

LEDALITE

Suspended
Direct/Indirect
3 T5

RESPONSE® airwave™



Project Name	
Spec Type	
Notes	

Order Guide

Some combinations of product options may not be available. Consult factory for assistance with your specification.

7706	F03			–	–	–	–	–
Product Series & Type	**Lamping**	**Lower Optics**	**Upper Optics**	**Run Length**	**Wiring**	**Voltage**	**Ballast**	**Color & Finish**
Sona Direct/Indirect	3 T5	P Semi-Specular Louver W White Louver	N None D 60% Down Kit G 80% Down Kit J 100% Down Kit Y 2 Down / 1 Up Kit Z 1 Down / 2 Up Kit	*Enter the total run length in feet (4ft increments)*	1 1 cct 2 2 cct 3 1 cct w/ Emergency cct 4 2 cct w/ Emergency cct 5 1 cct w/ Battery Pack 6 2 cct w/ Battery Pack 7 1 cct Dimming	1 120V 2 277V 3 347V	E Standard Ballast Consult website for ballast manufacturer information	W Standard White C Factory Color X Custom Color Consult website for color and finish options
		See details on reverse	See details on reverse	See details on reverse	Consult website for complete list of standard wiring options			

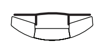
Mounting Hardware

Mount Type	Suspension Length
Consult separate mounting spec sheet for mount type options	*Enter distance from ceiling to top of fixture in inches*

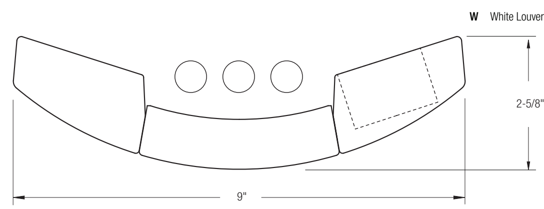
Upgrades & Accessories

Please indicate with check mark.

- ☐ Lamps Included
- ☐ Lamps Included and Installed
- ☐ Flat Endcap
  See details on reverse
- ☐ Dust Cover
  Only available with upper optics option N



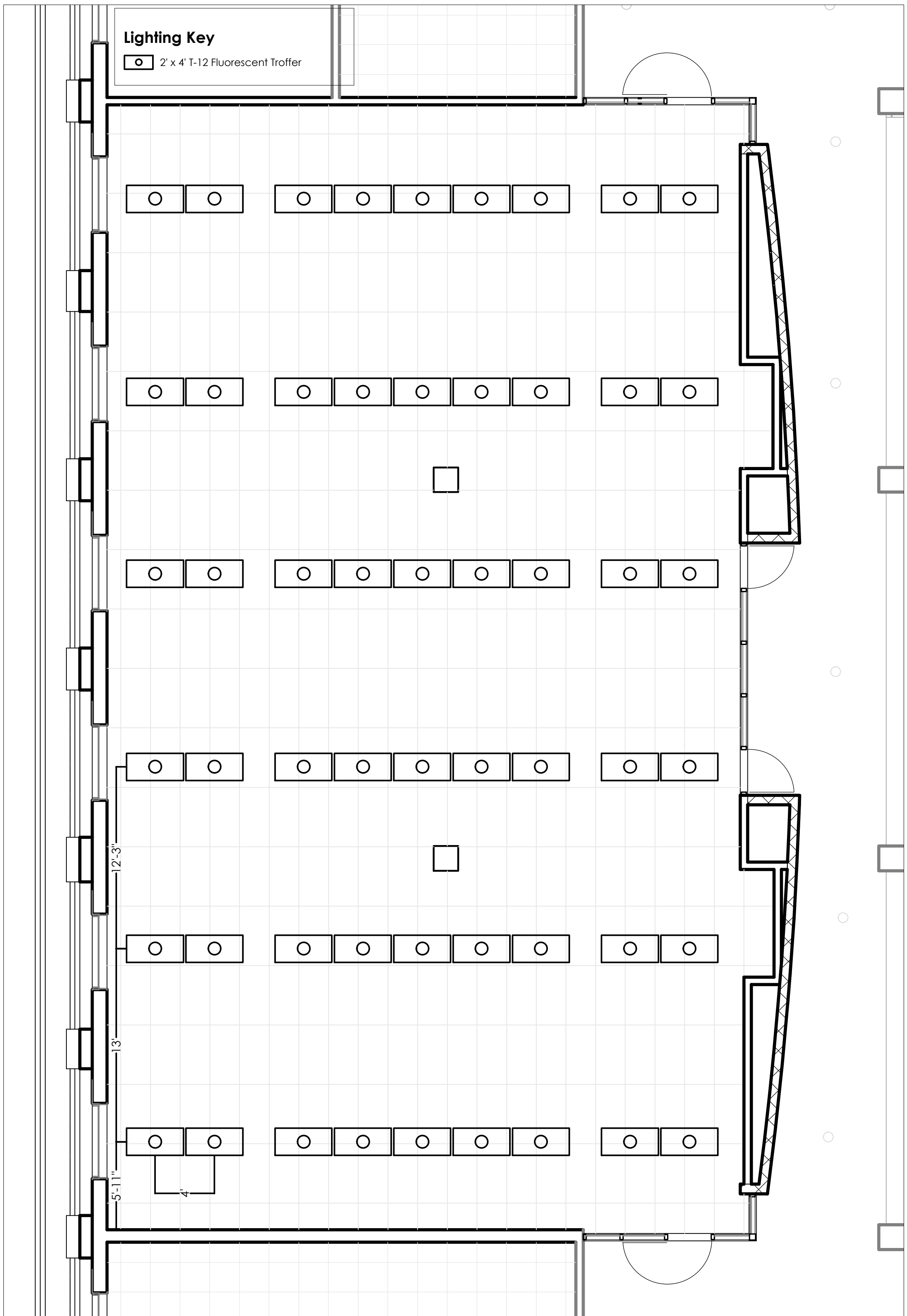
- ☐ Response Daylight (Integrated Controls)
  For details visit www.ledalite.com/response



 Phone: 604.888.6811 Fax: 800.665.5332 Web: www.ledalite.com Filename 7706F03WN.pdf Rev 1.2

Ledalite is a Philips group brand

PHILIPS

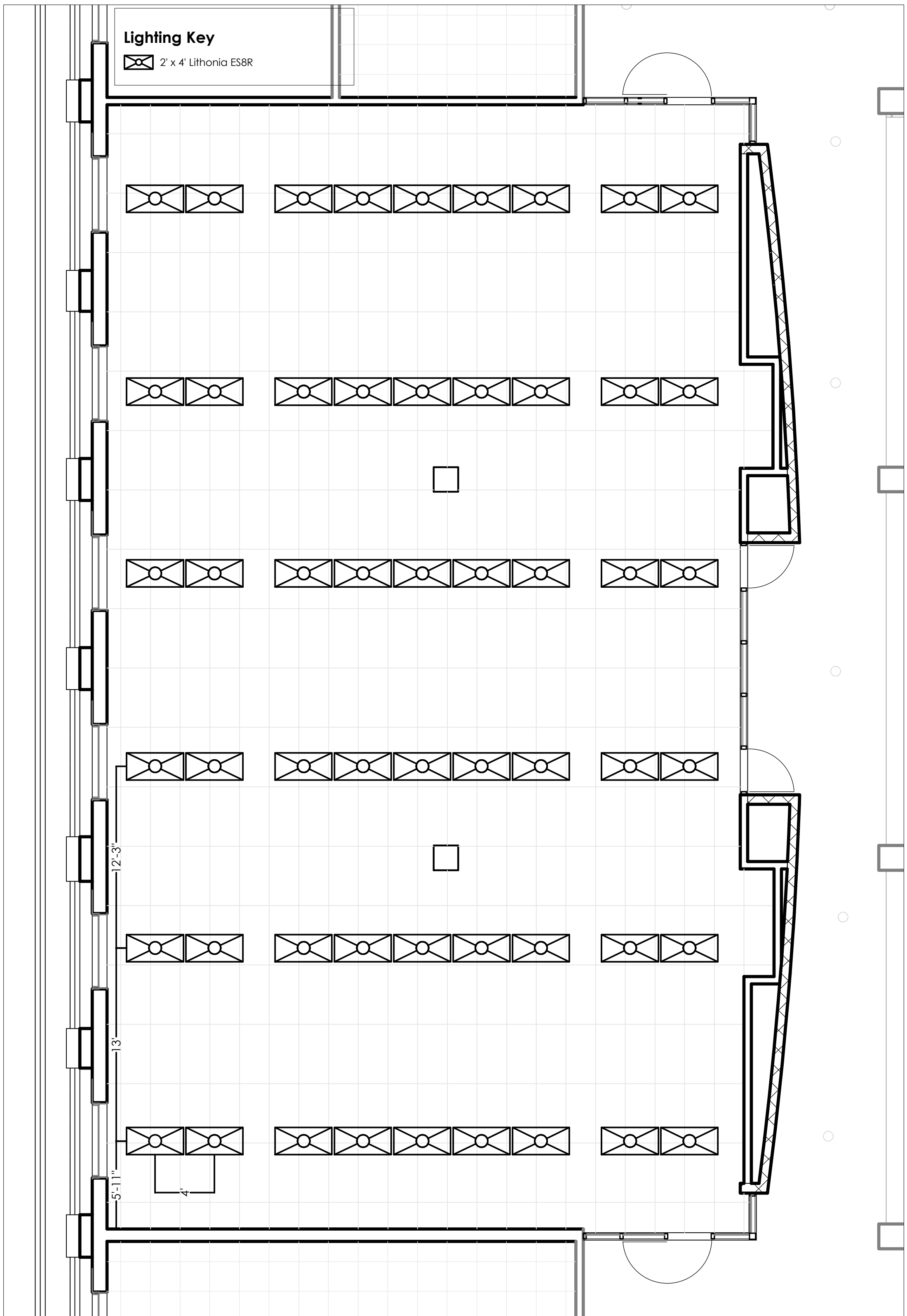


Scheme 1 Existing

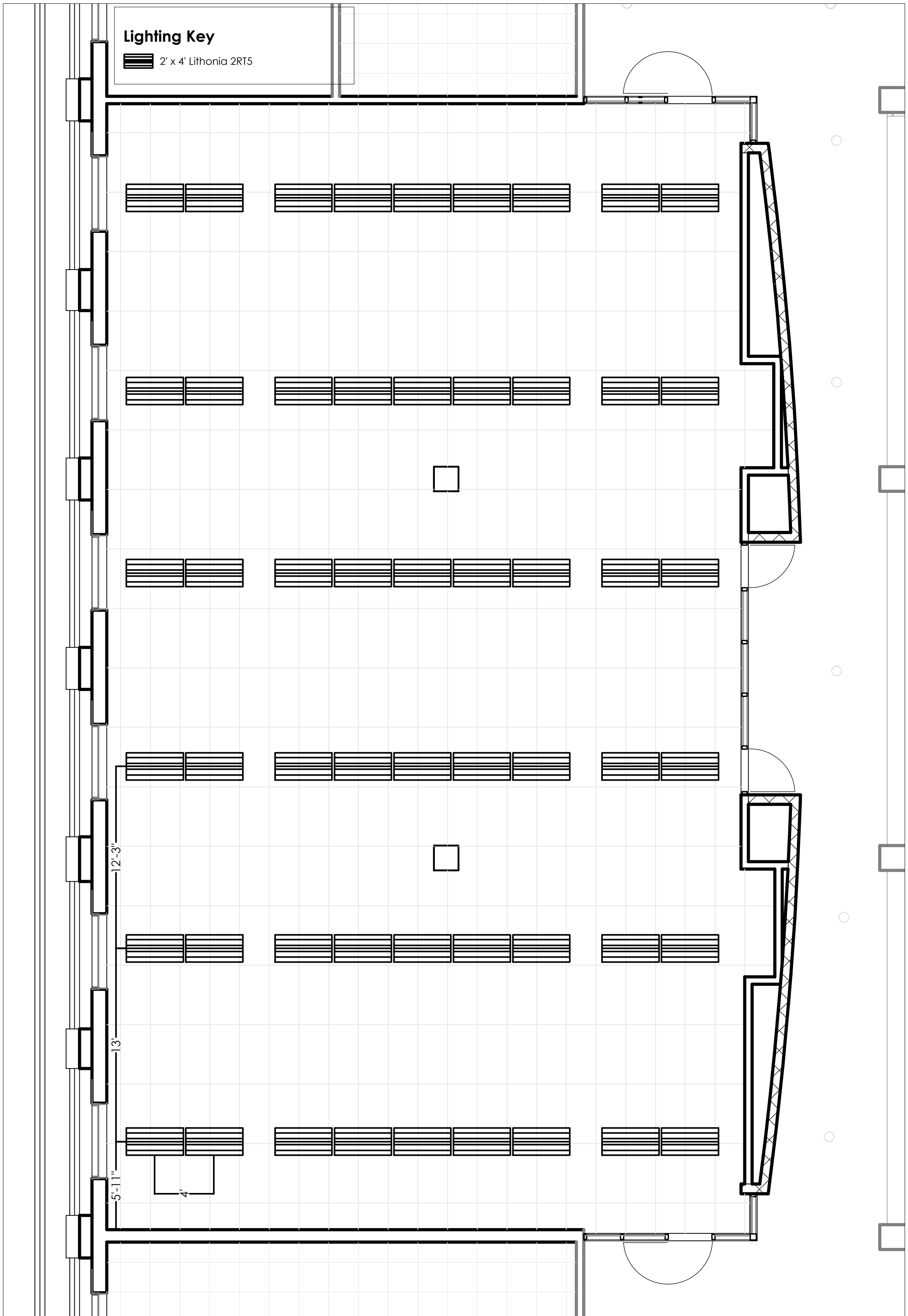
Appendix
p. 82

North:

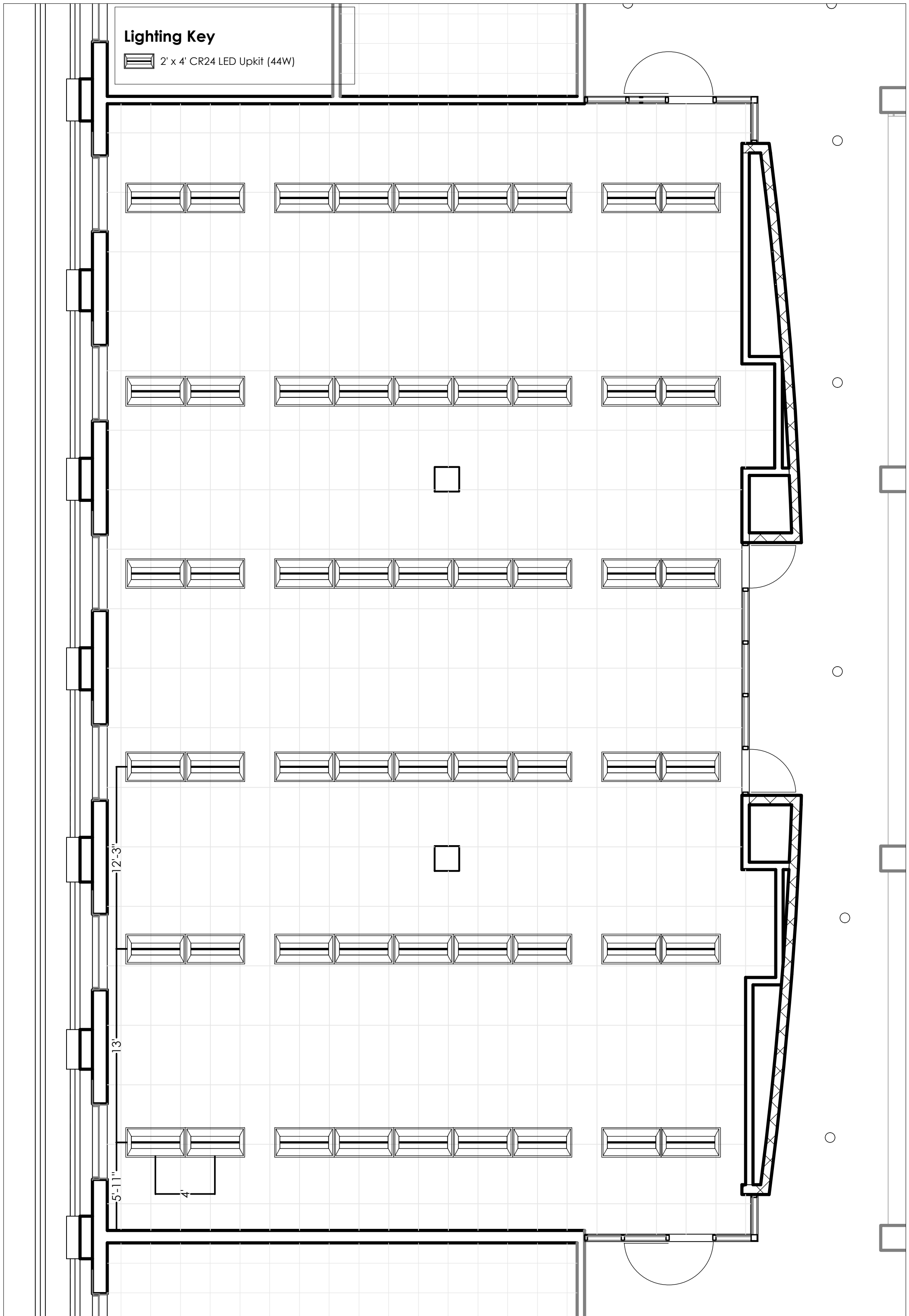
Scale: $\frac{3}{16}$" = 1'-0"



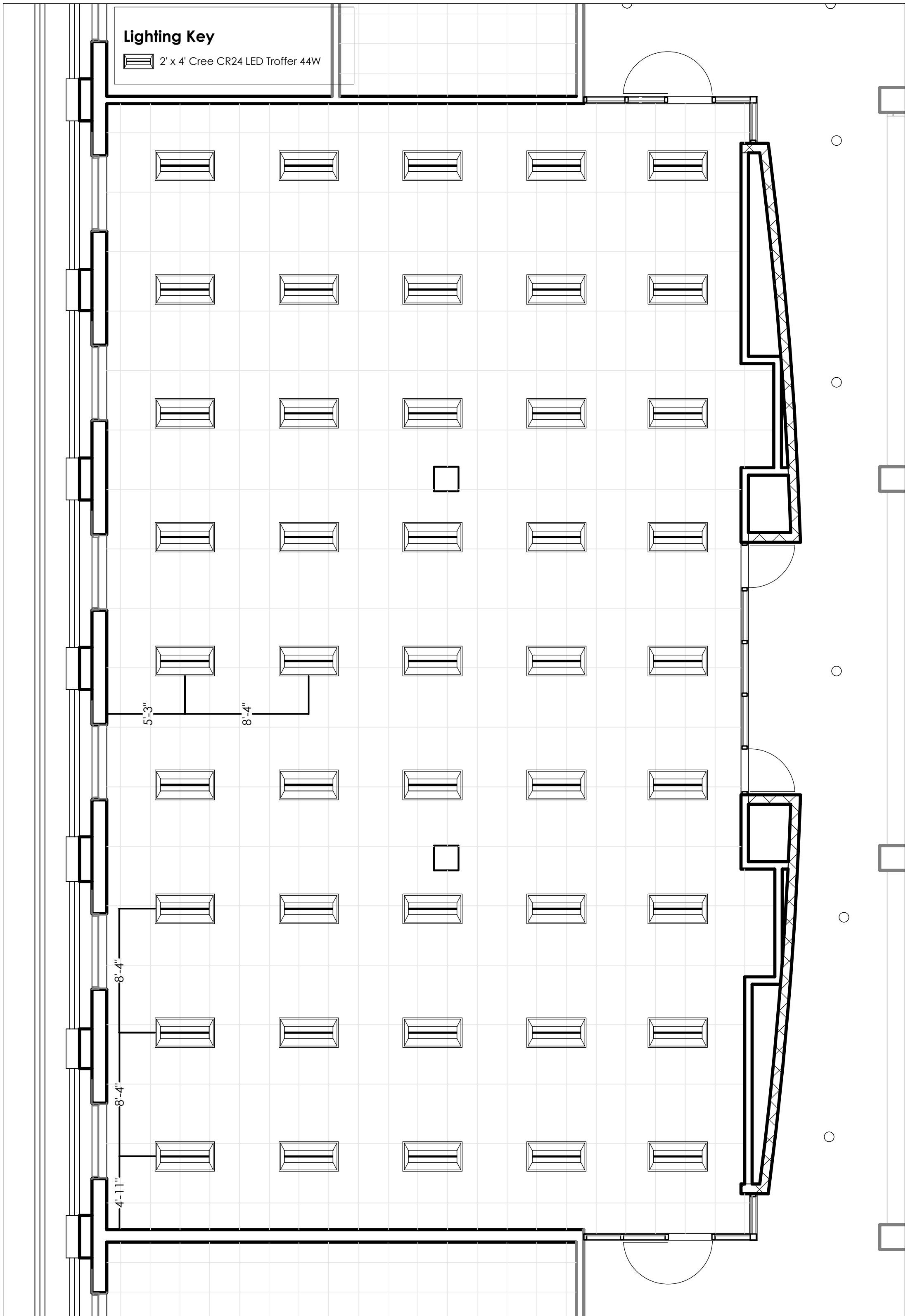
Scheme 2 T-8 Relamp	Appendix p 83	North:	Scale: $\frac{3}{16}$'' = 1'-0''



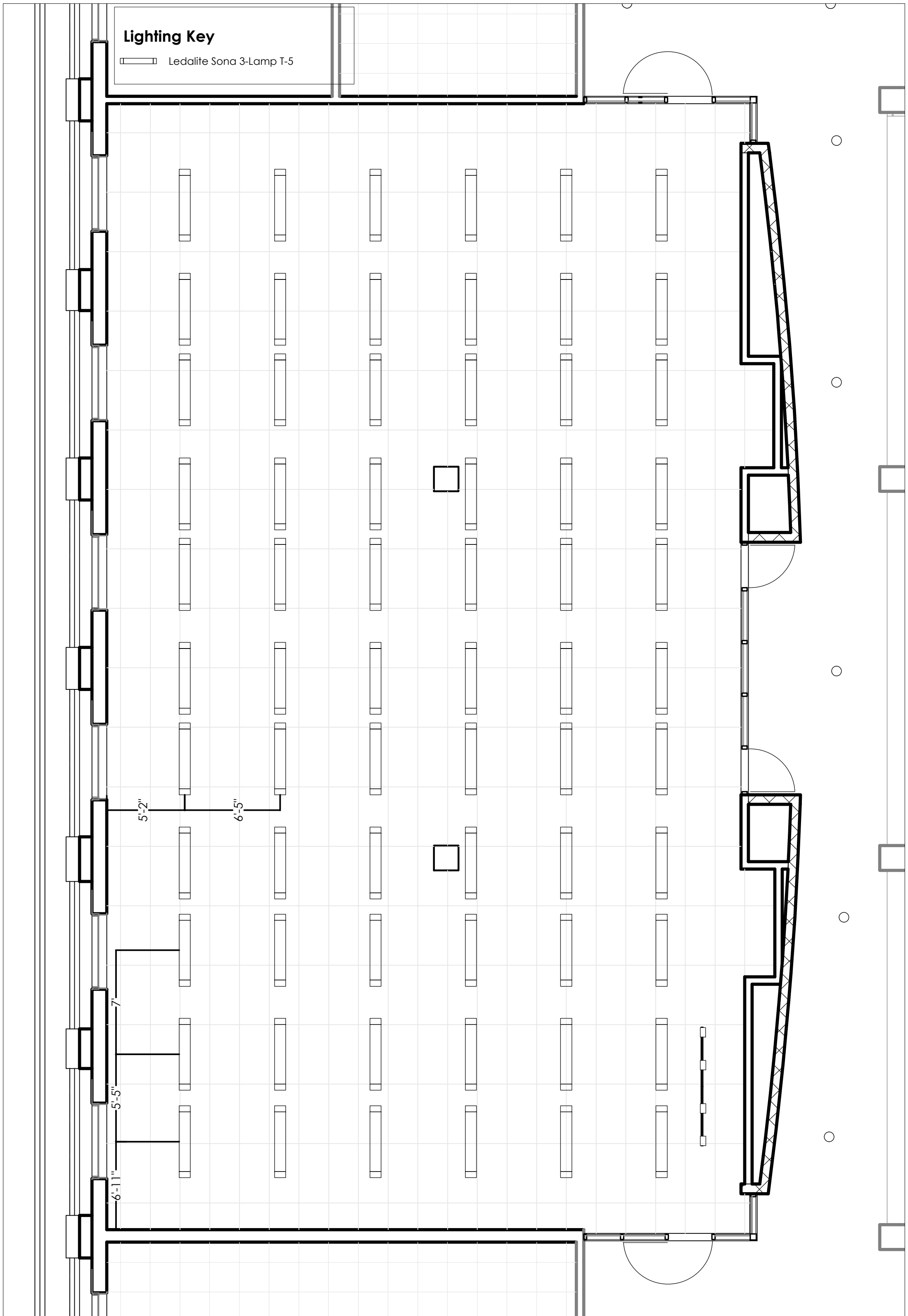
Scheme 2a T-5 Relamp	Appendix p 84	North:	Scale: $\frac{3}{16}$" = 1'-0"



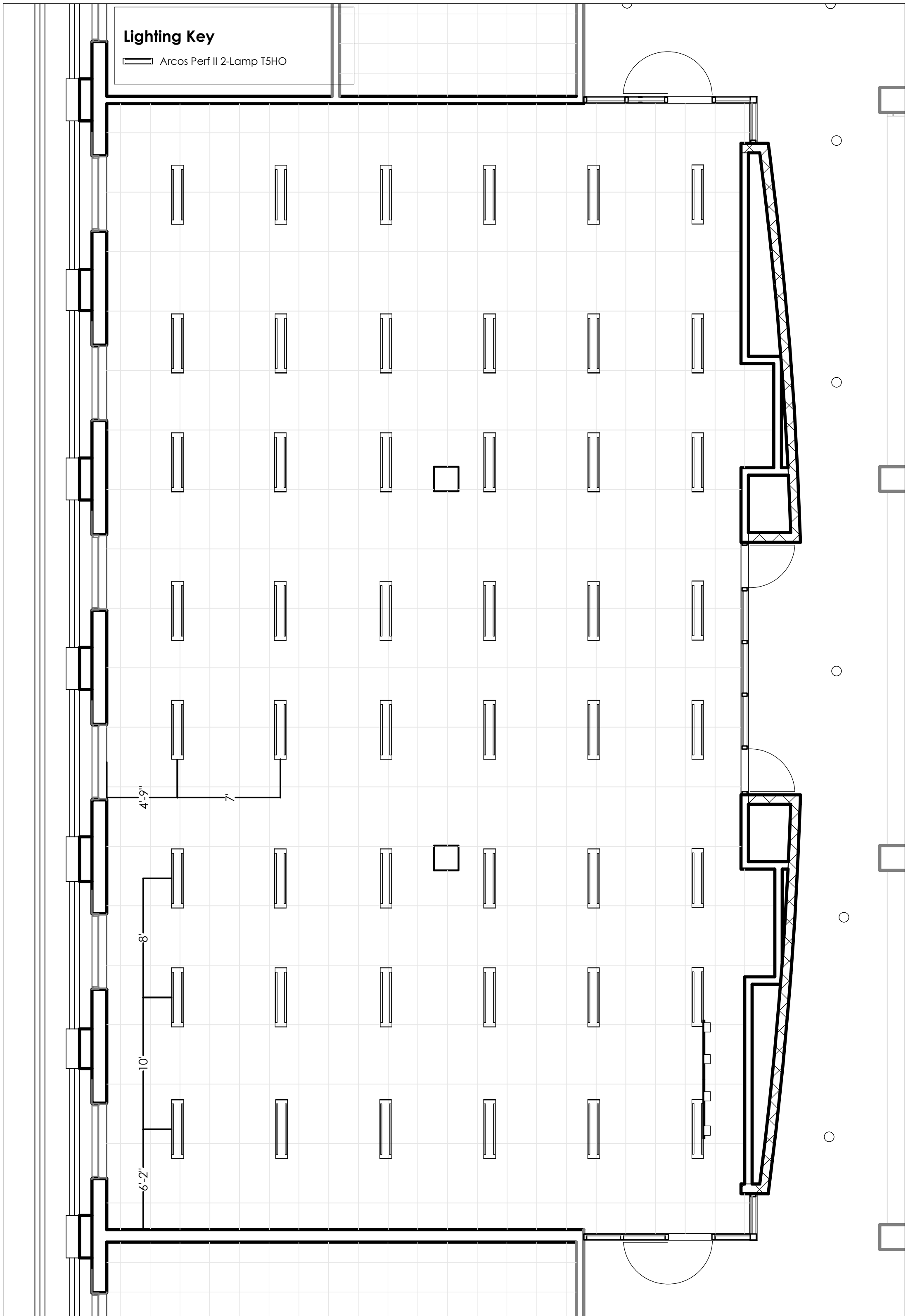
Scheme 2b LED Relamp	Appendix p 85	North:	Scale: $\frac{3}{16}$" = 1'-0"



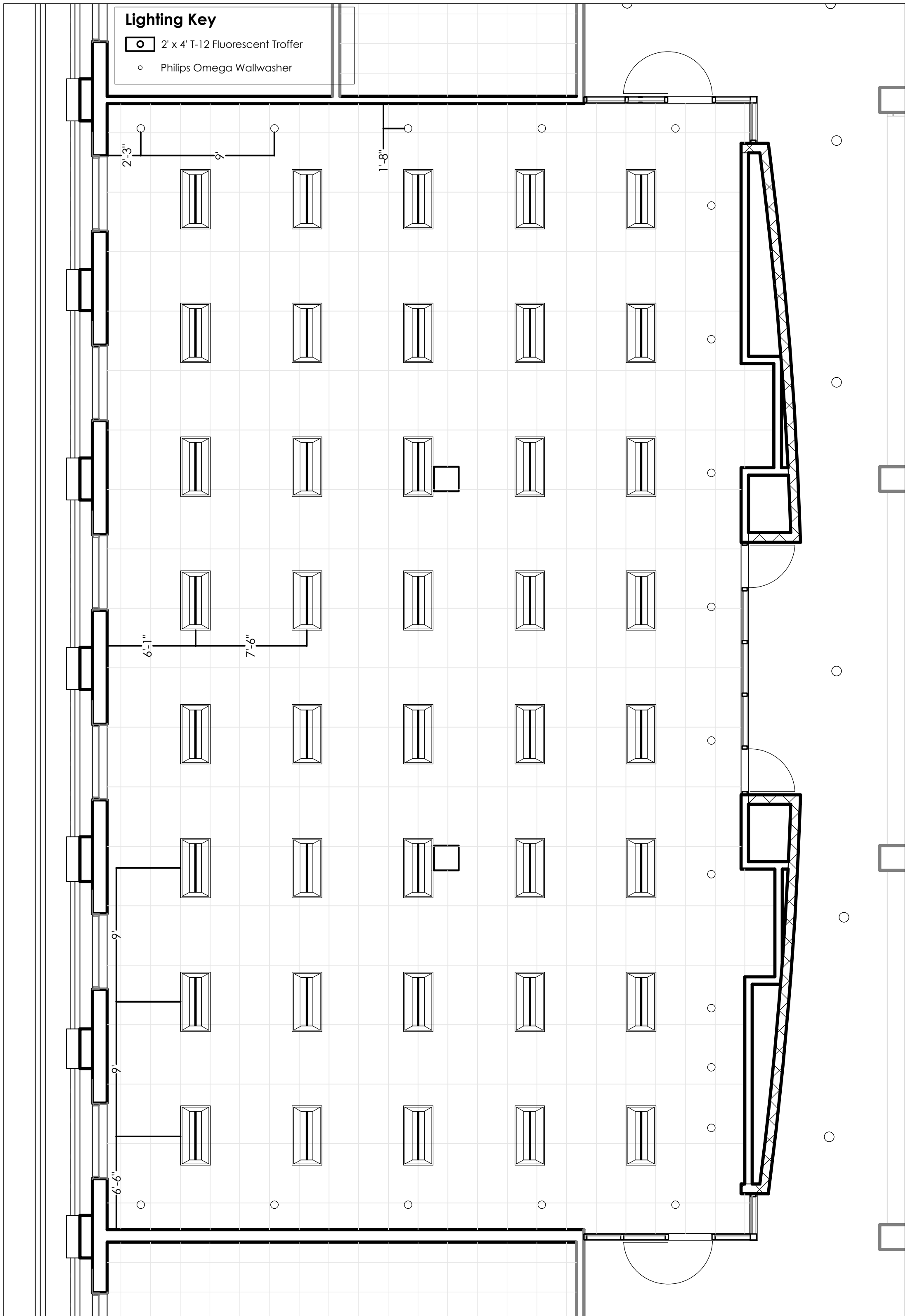
Scheme 3 LED+Spacing	Appendix p 86	**North:**	**Scale:** $\frac{3}{16}$" = 1'-0"



Scheme 4 Dir./Indir.+Task	Appendix p 87	**North:**	**Scale:** $\frac{3}{16}$" = 1'-0"



Scheme 4a Indirect+Task | Appendix p 88 | North: | Scale: $\frac{3}{16}$" = 1'-0"



Scheme 5 Multi-Scene	Appendix p 89	North:	Scale: $\frac{3}{16}$" = 1'-0"

Experiments In Artificial Lighting | Comparative Analysis Of Luminaire Typologies

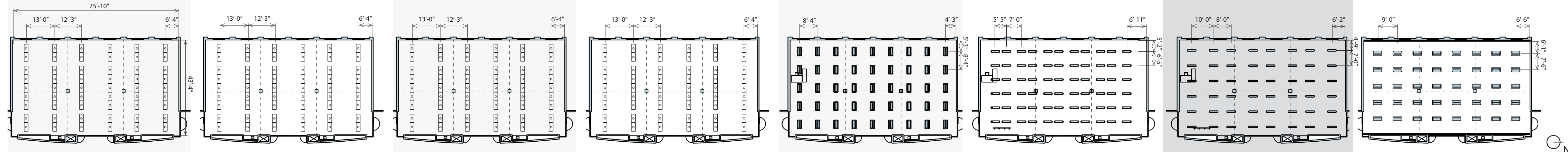
Raphael Tran | DArch Project | Spring 2013

Scheme No.	1 Existing Fluorescent	2 2'x4' T-8 Relamp	2a 2'x4' T-5 Relamp	2b 2'x4' LED Relamp
	3-Lamp, 35W T-12 2'x4'	Lithonia ES8R 2-Lamp, 32W T-8 2'x4'	Lithonia 2RT5 2-Lamp, 28W T-5 2'x4'	Cree CR24 LED Upkit 44W, 4000K, 2'x4'
Reflected Ceiling Plan	Power Density: 1.48 watts/sq. ft. (est.) No. of Luminaires: 54	Power Density: 0.77 watts/sq. ft. No. of Luminaires: 54	Power Density: 0.96 watts/sq. ft. No. of Luminaires: 54	Power Density: 0.71 watts/sq. ft. No. of Luminaires: 54
Horizontal Illuminance Analysis	Range: 8.1-88.1 fc Average: 44.53 fc Uniformity Ratio: 6.0 ✗ Baseline not met: overillumination	Range: 9.9-89.9 fc Average: 51.64 fc Uniformity Ratio: 5.2 ✗ Baseline not met: overillumination	Range: 8.1-88.1 fc Average: 45.30 fc Uniformity Ratio: 5.5 ✗ Baseline not met: overillumination	Range: 12-95 fc Average: 65.98 fc Uniformity Ratio: 5.4 ✗ Baseline not met: overillumination
Luminance Analysis	Range: 45.9-117.8 fL Contrast Ratio (Task to remote): 1:1 Contrast Ratio (Task to adjacent): 1:1 ✓ Baseline met	Range: 22.4-48.8 fL Contrast Ratio (Task to remote): 1.2:1 Contrast Ratio (Task to adjacent): 1:1 ✓ Baseline met	Range: 18.9-41.5 fL Contrast Ratio (Task to remote): 1:1 Contrast Ratio (Task to adjacent): 1:1 ✓ Baseline met	Range: 17.5-41.6 fL Contrast Ratio (Task to remote): 1.2:1 Contrast Ratio (Task to adjacent): 1:1 ✓ Baseline met
Annual Cost Projection	Total Initial Installation Cost: N/A Total Annual Energy Cost: $4,554.66 Total Annual Relamping Cost: $229.42 Total Maint. and Oper. Costs: $4,784.08 Potent. Annual Cost Savings: N/A	Total Initial Installation Cost: $8,792.10 Total Annual Energy Cost: $2,376.35 Total Annual Relamping Cost: $152.95 Total Maint. and Oper. Costs: $2,529.29 Potent. Annual Cost Savings: $2,254.79	Total Initial Installation Cost: $14,265.72 Total Annual Energy Cost: $2,970.43 Total Annual Relamping Cost: $71.28 Total Maint. and Oper. Costs: $3,041.71 Potent. Annual Cost Savings: $1,742.37	Total Initial Installation Cost: $7,829.46 Total Annual Energy Cost: $2,178.32 Total Annual Relamping Cost: $0.00 Total Maint. and Oper. Costs: $2,178.32 Potent. Annual Cost Savings: $2,605.76

Scheme No.	3 2'x4' LED Troffer	4 Direct/Indirect + Task	4a Indirect + Task	5 LED Troffer + Task
	Cree CR24 LED Troffer 44W, 4000K, 2'x4'	Ledalite Sona 3-Lamp, T-5 65% Up / 37% Down	Arcos Perf II 2-Lamp T5HO	Cree CR24 + Wallwash +Task 22W / Philips Omega
Reflected Ceiling Plan	Power Density: 0.59 watts/sq. ft. No. of Luminaires: 45	Power Density: 0.77 watts/sq. ft. No. of Luminaires: 66	Power Density: 0.47 watts/sq. ft. No. of Luminaires: 48	Power Density: 0.42 watts/sq. ft. No. of Luminaires: 40
Horizontal Illuminance Analysis	Range: 7.2-87.2 fc Average: 57.29 fc Uniformity Ratio: 7.9 ✗ Baseline not met: overillumination	Range: 8.1-61 fc Average: 30.90 fc Uniformity Ratio: 3.8 ✓ Baseline met	Range: 7-42 fc Average: 29.04 fc Uniformity Ratio: 4.1 ✓ Baseline met	Range: 5-102 fc Average: 31.89 fc Uniformity Ratio 6.3 ✗ Baseline not met: overillumination
Luminance Analysis	Range: 14.2-34.7 fL Contrast Ratio (Task to remote): 2:1 Contrast Ratio (Task to adjacent): 1:1 ✓ Baseline met	Range: 15.3-69.8 fL Contrast Ratio (Task to remote): 2:1 Contrast Ratio (Task to adjacent): 3:1 ✓ Baseline met	Range: 52.8-132.7 fL Contrast Ratio (Task to remote): 2:1 Contrast Ratio (Task to adjacent): 1:1 ✓ Baseline met	Range: 17.5-38.8 fL Contrast Ratio (Task to remote): 1.3:1 Contrast Ratio (Task to adjacent): 1:1 ✓ Baseline met
Annual Cost Projection	Total Initial Installation Cost: $16,243.11 Total Annual Energy Cost: $1,815.26 Total Annual Relamping Cost: $0.00 Total Maint. and Oper. Costs: $1,815.26 Potent. Annual Cost Savings: $2,968.82	Total Initial Installation Cost: $61,854.42 Total Annual Energy Cost: $2,450.32 Total Annual Relamping Cost: $130.68 Total Maint. and Oper. Costs: $2,581.00 Potent. Annual Cost Savings: $2,203.08	Total Initial Installation Cost: $35,875.50 Total Annual Energy Cost: $1,542.69 Total Annual Relamping Cost: $129.93 Total Maint. and Oper. Costs: $1,672.62 Potent. Annual Cost Savings: $3,111.46	Total Initial Installation Cost: $30,661.41 Total Annual Energy Cost: $1,458.35 Total Annual Relamping Cost: $107.29 Total Maint. and Oper. Costs: $2,126.72 Potent. Annual Cost Savings: $2,657.36

Reflected Ceiling Plan

The reflected ceiling plan shows the overall layout and types of luminaires used.



Rendered Perspective

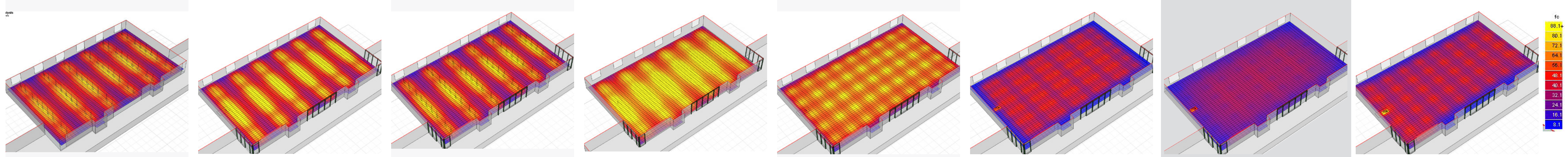
Provides a visualization of the space from the point of view of the user.

Horizontal Illuminance Analysis

Analysis of the lighting values that strikes the horizontal workplane.

Baseline: 25-30 fc average illuminance
50-100 fc on work surfaces

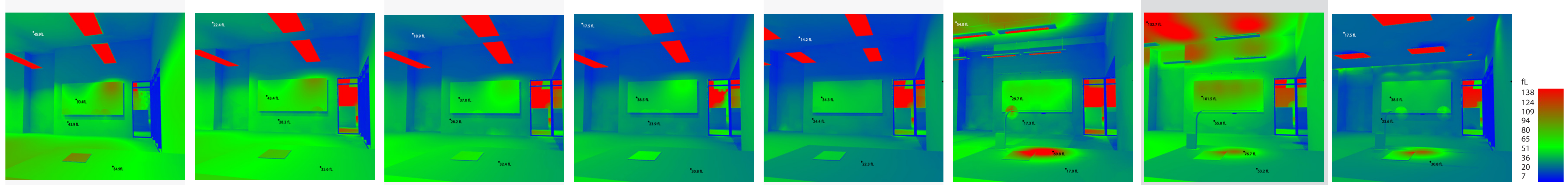
Average-to-minimum uniformity ratio of 4 or lower.



Luminance Analysis

Analysis of lighting levels that reach a user's eyes.

Goal: Minimal Luminance ratio between work surface and surroundings.



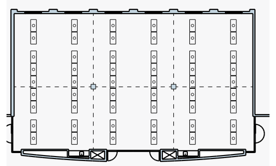
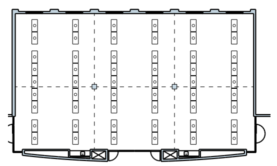
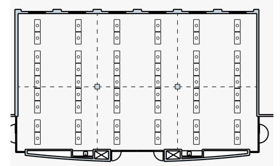
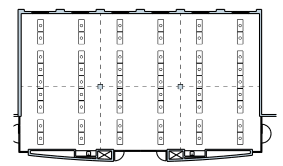
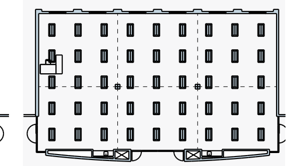
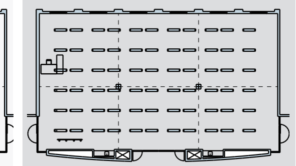
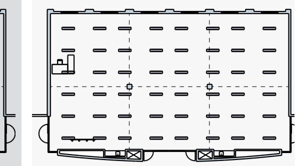
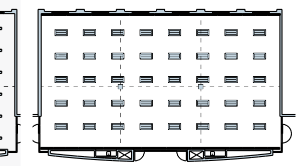
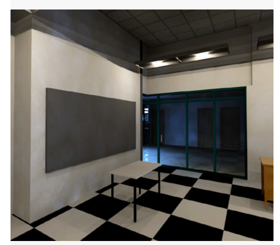
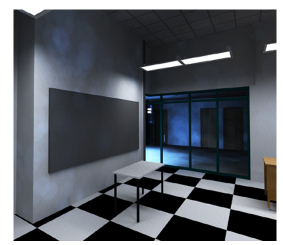
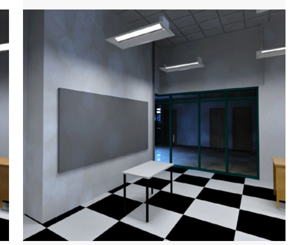
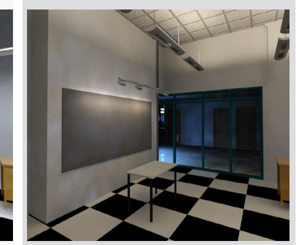
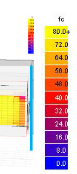
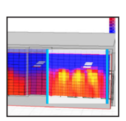
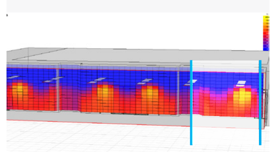
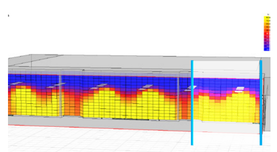
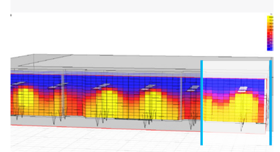
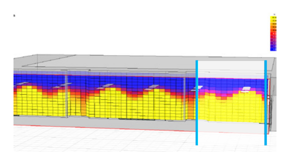
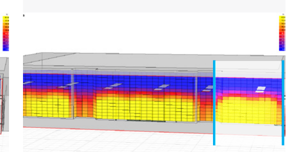
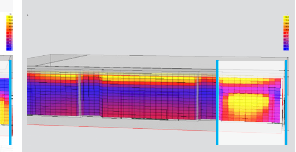
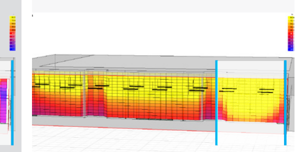
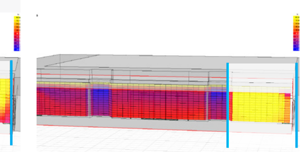
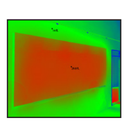
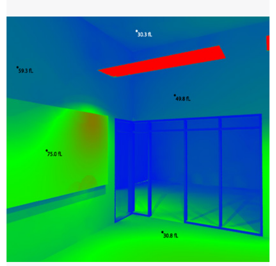
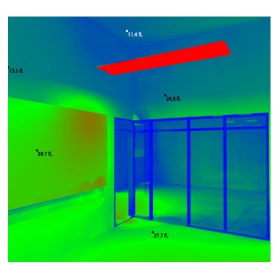
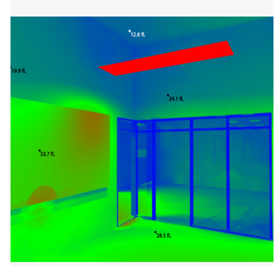
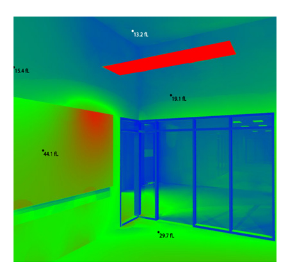
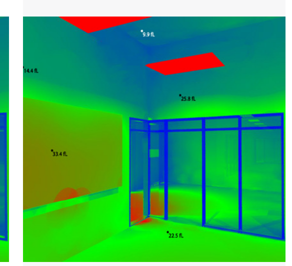
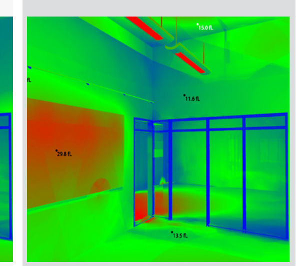
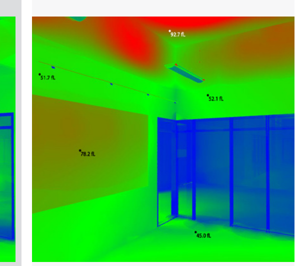
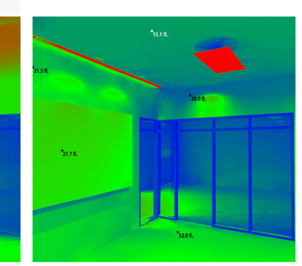
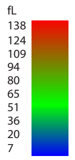
Annual Cost Projection

Projection of installation costs, annual energy, relamping, and operating costs.

AMBIENT+TASK

Experiments In Artificial Lighting | Comparative Analysis Of Luminaire Typologies

PRESENTATION SPACE

Scheme No.	**1** Existing Fluorescent 3-Lamp, 35W T-12 2'x4'	**2** 2'x4' T-8 Relamp Lithonia ES8R 2-Lamp, 32W T-8 2'x4'	**2a** 2'x4' T-5 Relamp Lithonia 2RT5 2-Lamp, 28W T-5 2'x4'	**2b** 2'x4' LED Relamp Cree CR24 LED Upkit 44W, 4000K, 2'x4'	**3** 2'x4' LED Troffer Cree CR24 LED Troffer 44W, 4000K, 2'x4'	**4** Direct/Indirect + Task Ledalite Sona 3-Lamp, T-5 65% Up / 37% Down	**4a** Indirect + Task Arcos Perf II 2-Lamp T5HO	**5** LED Troffer + Task Cree CR24 + Wallwash +Task 22W / Philips Omega
Reflected Ceiling Plan The reflected ceiling plan shows the overall layout and types of luminaires used.	 Power Density: 1.48 watts/sq. ft. (est.) No. of Luminaires: 54	 Power Density: 0.77 watts/sq. ft. No. of Luminaires: 54	 Power Density: 0.96 watts/sq. ft. No. of Luminaires: 54	 Power Density: 0.71 watts/sq. ft. No. of Luminaires: 54	 Power Density: 0.59 watts/sq. ft. No. of Luminaires: 45	 Power Density: 0.77 watts/sq. ft. No. of Luminaires: 66	 Power Density: 0.47 watts/sq. ft. No. of Luminaires: 48	 Power Density: 0.42 watts/sq. ft. No. of Luminaires: 40
Rendered Perspective Provides a visualization of the space from the point of view of the user.								 
Vertical Illuminance Analysis Analysis of the lighting values that strikes the horizontal workplane. **Baseline:** minimum 30 fc average uniformity of 2:1 or better. **Best-Case:** 	 Range: 5-80 fc Average Value: 25.97 fc Uniformity Ratio: 5.1 Baseline not met: • under-illuminance	 Range: 8-100 fc Average Value: 42.79 fc Uniformity Ratio: 5.3 Baseline not met: • nonuniform illuminance	 Range: 5-100 fc Average Value: 33.79 fc Uniformity Ratio: 6.7 Baseline not met: • nonuniform illuminance	 Range: 10-180 fc Average Value: 55.70 fc Uniformity Ratio: 5.6 Baseline not met: • nonuniform illuminance	 Range: 9-100 fc Average Value: 31.68 fc Uniformity Ratio: 3.5 Baseline not met: • nonuniform illuminance (along entire wall surface)	 Range: 8-102.8 fc Average Value: 32.91 fc Uniformity Ratio: 4.1 Baseline not met: • nonuniform illuminance (along entire wall surface)	 Range: 13-103 fc Average Value: 31.03 fc Uniformity Ratio: 2.3 Baseline met	 Range: 8-203 fc Average Value: 49.59 fc Uniformity Ratio: 6.1 Baseline not met: • nonuniform illuminance (along entire wall surface)
Luminance Analysis Analysis of lighting levels that reach a user's eyes. **Baseline:** Contrast ratio between pin-up board and surrounding wall of at least 2:1, uniform luminance across board. **Best-Case:** 	 Range: 30.3-75.0 fL Contrast Ratio: 1.3:1 Baseline not met: • nonuniform luminance • contrast ratio too low	 Range: 11.4-39.7 fL Contrast Ratio: 3:1 Baseline not met: • nonuniform luminance	 Range: 12.6 - 33.7 fL Contrast Ratio: 2:1 Baseline not met: • nonuniform luminance	 Range: 13.2 - 44.1 fL Contrast Ratio: 3:1 Baseline not met: • nonuniform luminance	 Range: 9.9-33.4 fL Contrast Ratio: 2.3:1 Baseline not met: • nonuniform luminance	 Range: 11.6-29.8 fL Contrast Ratio: 2:1 Baseline met	 Range: 45.0-92.7 fL Contrast Ratio: 2:1 Baseline not met: • nonuniform luminance	 Range: 15.1-32.0 fL Contrast Ratio: 1:1 Baseline not met: • nonuniform luminance • contrast ratio too low 

Parameters	Scheme 1 (Existing)	Scheme 2	Scheme 2a	Scheme 2b	Scheme 3	Scheme 4		Scheme 4a		Scheme 5		
Luminaire Type	2'x4' Troffer	Lithonia ES8R	Lithonia 2RT5	Cree CR24 Relamp	Cree CR24 LED	Ledalite Sona	Task Lamp	Arcos Perf II	Task Lamp	Cree CR 24	Phillips Omega	Task Lamp
Number of Lamps/Luminaire	3	2	2	N/A	N/A	3	N/A	2	N/A	N/A	1	N/A
Watts per Luminaire	92	48	60	44	44	39	4	33	4	22	36	4
Number of Luminaires	54	54	54	54	45	66	60	48	60	40	17	60
Annual Operating Hours	3120	3120	3120	3120	3120	3120	1300	3120	1300	3120	3120	1300
Initial Costs												
Luminaire Cost Per Unit	N/A	$79.99	$185.00	$79.99	$269.99	$669.10	$200.00	$399.99	$200.00	$224.99	$134.99	$200.00
Lamp Cost Per Unit	$10.58	$10.58	$7.09	N/A	N/A	$7.09	N/A	$7.09	N/A	N/A	$5.80	N/A
Labor/Installation Cost (at $48.63/hr)	N/A	$2,626.02	$2,626.02	$2,626.02	$3,209.58	$3,209.58	N/A	$3,209.58	N/A	$4,522.59	$1,732.04	N/A
Additional Material/Labor Cost (addn wiring, controls)	N/A	$883.98	$883.98	$883.98	$883.98	$1,080.42	N/A	$785.76	N/A	$654.80	$451.75	N/A
Subtotal Initial Cost							$12,000.00		$12,000.00		$4,484.42	$12,000.00
Total Initial Cost	**N/A**	**$8,972.10**	**$14,265.72**	**$7,829.46**	**$16,243.11**		**$61,854.42**		**$35,875.50**			**$30,661.41**
Maintenance and Operating Cost												
Electric Demand Rate ($/kW/mo)	$11.69	$11.69	$11.69	$11.69	$11.69	$11.69		$11.69		$11.69	$11.69	
Peak Demand (kW)	4.968	2.592	3.24	2.376	1.98	2.574		1.584		0.88	0.612	
Annual Demand Charge	$59.62	$31.10	$38.88	$28.51	$23.76	$30.89		$19.01		$10.56	$7.34	
Electric Energy Rate ($/kWh)	$0.29	$0.29	$0.29	$0.29	$0.29	$0.29	$0.29	$0.29	$0.29	$0.29	$0.29	$0.29
Annual Energy Cost	$4,495.05	$2,345.24	$2,931.55	$2,149.80	$1,791.50	$2,328.96	$90.48	$1,433.20	$90.48	$796.22	$553.74	$90.48
Subtotal Annual Cost							$90.48		$90.48		$561.08	$90.48
Total Annual Cost - Energy and Demand	**$4,554.66**	**$2,376.35**	**$2,970.43**	**$2,178.32**	**$1,815.26**		**$2,450.32**		**$1,542.69**			**$1,458.35**
Avg Rated Lamp Life (Hrs)	24,000	24,000	35,000	50,000	50,000	35,000	50,000	35,000	50,000	50,000	12,000	50,000
Quantity Lamps Replaced per Yr	21	14	10	N/A	N/A	18	N/A	18	N/A	N/A	18	N/A
Hours to Replace Each Lamp	0.08	0.08	0.08	0.08	0.08	0.08	N/A	0.08	N/A	0.08	0.08	N/A
Labor Cost to Replace Lamps	$3.92	$3.92	$3.92	$3.92	$3.92	$3.92	N/A	$3.92	N/A	$3.92	$3.92	N/A
Total Annual Relamping Cost	**$229.42**	**$152.95**	**$71.28**	**$0.00**	**$0.00**	**$130.68**	**$0.00**	**$129.93**	**$0.00**	**$0.00**	**$107.29**	**$0.00**
Subtotal Maintenance and Operating Costs per Year						$2,581.00		$1,672.62		$1,458.35	$668.38	
Total Maintenance and Operating Costs per Year	**$4,784.08**	**$2,529.29**	**$3,041.71**	**$2,178.32**	**$1,815.26**		**$2,581.00**		**$1,672.62**			**$2,126.72**
Potential Operating Cost Savings per Year	N/A	$2,254.79	$1,742.37	$2,605.76	$2,968.82		$2,203.08		$3,111.46			$2,657.36
Percentage of Potential Savings per Year	N/A	52.87%	63.58%	45.53%	37.94%		53.95%		34.96%			44.45%

NOTES:

*Energy Rates and Demand Rates derived from HECO Rates Schedule J for General Service (Effective Sept 1, 2012)

*Labor costs derived from RSMeans national average construction costs for labor and additional materials.

*Luminaire pricing found at: http://www.goodmart.com/products/

*Average Rated Lamp Life from manufacturer information. Values are estimated and can vary depending on usage cycles.

*Operating hours assumes 10h day, 6 days/wk, 52 wks/yr

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